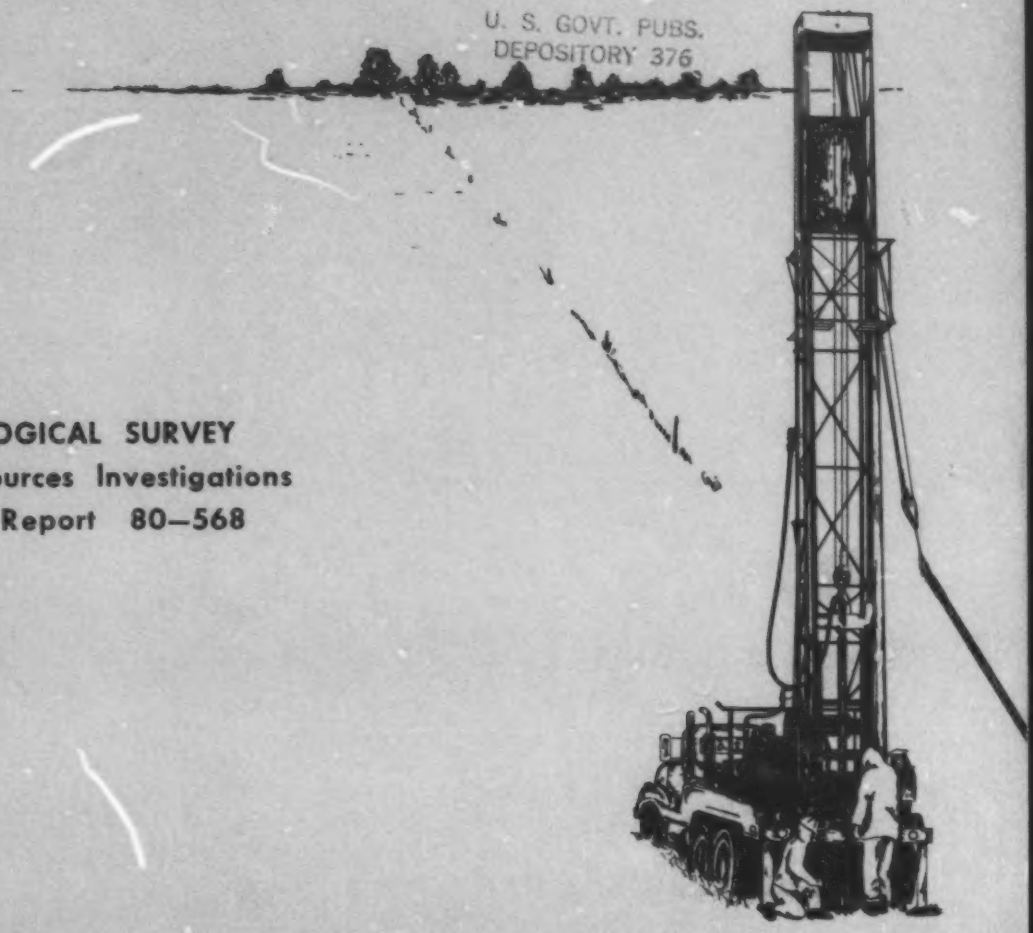
80-568

GROUND–WATER APPRAISAL IN NORTHWESTERN BIG STONE COUNTY, WEST–CENTRAL MINNESOTA

NEWARK PUBLIC LIBRARY

DEC 11 1980

U. S. GOVT. PUBS.
DEPOSITORY 376



U. S. GEOLOGICAL SURVEY

Water–Resources Investigations
Open–File Report 80–568

Prepared in cooperation with the
Minnesota Department of Natural Resources, and
Big Stone County Ground–Water Steering Committee

I 19.76:

GROUND-WATER APPRAISAL IN NORTHWESTERN BIG STONE COUNTY, WEST-CENTRAL MINNESOTA

By W. G. Soukup

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations

Open-File Report 80-568

Prepared in cooperation with the

Minnesota Department of Natural Resources, and

Big Stone County Ground-Water Steering Committee

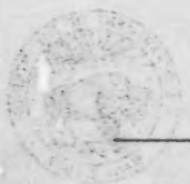
1980

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director



Open-File Report

For additional information write to:

U.S. Geological Survey
702 Post Office Building
St. Paul, Minnesota 55101

CONTENTS

	Page
Conversion factors	v
Abstract	1
Introduction	2
Purpose and scope	2
Location	2
Previous investigations	2
Methods of investigation	4
Test-hole numbering system	4
Geology	7
Bedrock deposits	7
Glacial deposits	12
Hydrology	16
Surficial outwash aquifer	16
Yield	16
Buried outwash aquifers	16
Statistical method of mapping buried outwash	22
Aquifer test	24
Cretaceous aquifers	27
Water quality	27
Conclusions	31
References	32

ILLUSTRATIONS

Figure 1.	Map of Minnesota showing location of Big Stone County and project area	3
2.	Map showing location of deep test holes, observation wells, and trace of geologic sections	5
3.	Diagram showing test-hole numbering system	6
4.	Diagram showing the correlation of bedrock units in the Upper Cretaceous Series in southwestern Minnesota	8
5.	Diagram showing the log of test hole BS-15, typical of Cretaceous rocks overlain by drift	9
6.	Geologic section A-A' showing the stratigraphic relationships associated with buried aquifers	10

ILLUSTRATIONS

Page

Figure 7. Map showing contours of the Cretaceous surface..... 13

8. Generalized fence diagram of northwestern Big Stone County, Minnesota..... 14

9. Map showing generalized surficial geology..... 17

10. Map showing saturated thickness of surficial outwash..... 18

11. Map showing transmissivity of surficial outwash..... 19

12. Map showing water-table configuration in northwestern Big Stone County..... 20

13. Map showing theoretical maximum yield of wells in the surficial-outwash aquifer..... 21

14. Map showing statistical distribution of sand units in drift, 4 or more feet thick..... 23

15. Graph of drawdown and recovery curves for well BS-28..... 25

16. Diagram comparing barometric changes to water-level changes in the buried outwash aquifer..... 26

17. Diagram comparing water-quality data from eight samples in surfical outwash, buried outwash, and Cretaceous aquifers..... 29

18. Diagram showing the suitability of ground water for irrigation, in terms of sodium-adsorption ratio and specific conductance..... 30

TABLES

Table 1. Chemical analyses of water from surficial outwash, buried outwash, and Cretaceous aquifers..... 28

2. Geologic logs of deep test holes..... 34

CONVERSION FACTORS

The following factors may be used to convert the inch-pound units published herein to the International System of units (SI).

Multiply	By	To obtain
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
foot per day (ft/day)	0.3048	meter per day (m/day)
foot squared per day (ft^2/day)	0.0929	meter squared per day (m^2/day)
cubic foot per second (ft^3/s)	0.2832	cubic meter per second (m^3/s)

National Geodetic Vertical Datum of 1929 (NGVD of 1929).

A geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada, formerly called "mean sea level". The datum was derived from the average sea level over a period of many years at 26 tide stations along the Atlantic, Gulf of Mexico, and Pacific Coasts.

GROUND-WATER APPRAISAL IN NORTHWESTERN BIG STONE COUNTY, WEST-CENTRAL MINNESOTA

By W. G. Soukup

ABSTRACT

The development of ground water for irrigation in northwestern Big Stone County has not kept up with development in other irrigable areas of the State. This is due, in part, to the absence of extensive surficial aquifers and the difficulty in locating buried aquifers.

Test augering south of Beardsley outlined a small surficial aquifer that consists of outwash deposits of sand and gravel. The aquifer is elongate, trending northeast-southwest, with a maximum saturated thickness of 42 feet and an areal extent of about 5 square miles.

Deep test drilling showed that small buried outwash aquifers occur over much of the project area. The 2-mile spacing between test holes, however, was too great to permit correlation of the buried aquifers.

A major buried outwash aquifer, east of Beardsley, consists of 130 feet of fine, uniform quartz sand. The aquifer lies in a steep-sided northwest-southeast trending valley eroded in bedrock and is overlain by 130 feet of clayey till. Pumping-test results indicate that its transmissivity ranges from 10,800 to 13,400 feet squared per day, and that the storage coefficient ranges from 0.0001 to 0.002. Recharge to the aquifer was negligible during 1979.

Two Cretaceous aquifers, the Codell Sandstone Member of the Carlile Shale and the Greenhorn Formation, underlie the area, but little is known about these aquifers.

Samples of water were collected for chemical analysis from wells in the surficial outwash, buried outwash, and Cretaceous aquifers. With the exception of nitrate, the greatest difference in chemical quality was between samples from the buried outwash and Cretaceous aquifers. Water from Cretaceous aquifers is softer than water from the outwash aquifers, but contains concentrations of sodium and boron that are high enough to damage soils and crops if used for irrigation. Nitrate concentrations exceeded the Minnesota Pollution Control Agency's recommended limits for drinking water in one sample from the surficial aquifer.

INTRODUCTION

During 1979, there were only two irrigation centers in northwestern Big Stone County. Unlike the extensive sand plains of central Minnesota, surficial outwash deposits are small in areal extent, and the location of dependable water supplies is difficult to predict. Outwash aquifers are buried by thick layers of lake clay and(or) clayey till and are seldom of great areal extent or thickness.

Purpose and Scope

The purpose of this study was to evaluate the ground-water resources of northwestern Big Stone County. This was accomplished by determining the occurrence and hydrologic characteristics of the surficial and buried outwash aquifers. Specifically, this entailed (1) mapping the areal extent and thickness of the surficial sands by augering, (2) mapping the areal extent and thickness of the buried aquifers by deep test drilling, (3) determining hydrologic properties of aquifers from pumping tests and drill cuttings, (4) determining the quality of water, and (5) establishing a network of observation wells to monitor the effects of ground-water development on water levels and storage in outwash aquifers.

The report includes hydrologic data such as lithologic logs, geophysical logs, results of water-quality analyses, and interpretations based upon the data.

Location

The study area is in northwestern Big Stone County, 95 miles south of Moorhead, Minn. (fig. 1). It encompasses 65 mi^2 and is delineated in part by State and county lines and in part by soil types reported by the Big Stone County Soil Conservation Service (1963).

The Minnesota State border parallels Big Stone Lake and defines the southern and western boundaries. The Traverse County line is the northern border. The irregular eastern boundary (fig. 1) represents the contact between the droughty soils of the project area and the poorly drained soils to the east.

Previous Investigations

An early description of the glacial history of Big Stone County is presented by Leverett (1932). In a later report by Sims and Morey (1972), Matsch (p. 548) gives a lithologic description of the various till sheets as well as a historical outline of the county.

Thiel (1944) gives a brief summary of the occurrence of ground water as part of his southern-Minnesota reconnaissance. A more detailed study of the availability of ground water was made by Cotter and others (1966).

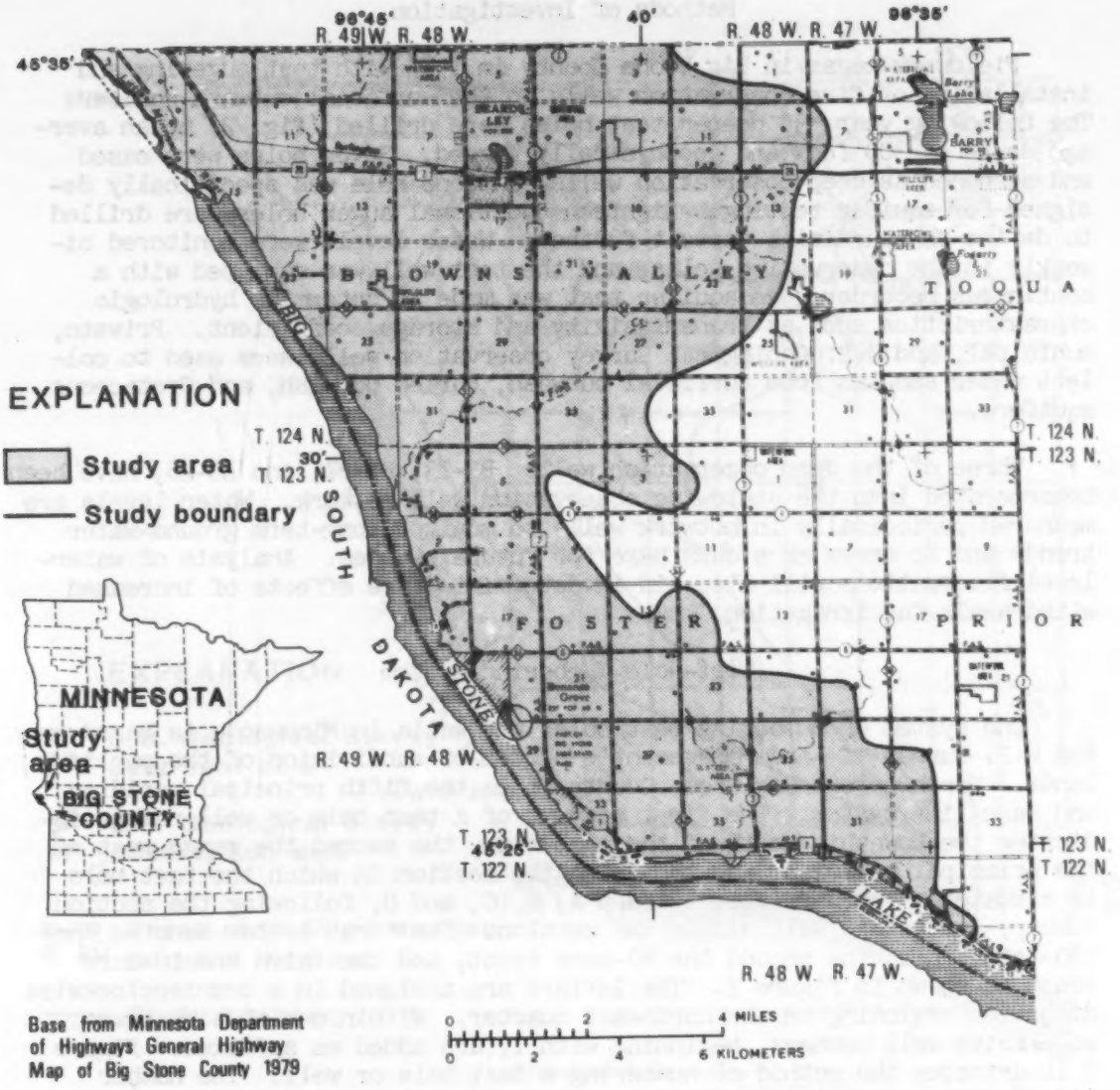


Figure 1.--Location of Big Stone County and project area

Methods of Investigation

Fieldwork began in Big Stone County in 1977 with test augering and installation of five observation wells in the surficial outwash aquifer. The following year, 30 deeper test holes were drilled (fig. 2) to an average depth of 300 feet and geophysically logged. Seven holes were cased and screened as deep observation wells, and one hole was specifically designed for aquifer testing. Eighteen additional auger holes were drilled to define the surficial deposit further. Water levels were monitored biweekly in the observation wells, and the test well was equipped with a continuous recorder. An aquifer test was made to determine hydrologic characteristics such as transmissivity and storage coefficient. Private, municipal, and U.S. Geological Survey observation wells were used to collect water samples from surficial outwash, buried outwash, and Cretaceous aquifers.

Three of the deep observation wells, BS-23, BS-27, and BS-28, have been incorporated into the statewide observation well network. Water levels are measured periodically in network wells to monitor long-term ground-water trends and to serve as a data base for future studies. Analysis of water-level fluctuations will also aid in determining the effects of increased withdrawals for irrigation.

Test-Hole Numbering System

The system of numbering test holes and wells in Minnesota is based on the U.S. Bureau of Land Management's system of subdivision of the public lands. Northwestern Big Stone County is in the fifth principal meridian and base-line system. The first segment of a test hole or well number indicates the township north of the base line, the second the range west of the principal meridian, and the third the section in which the test hole is situated. The uppercase letters A, B, C, and D, following the section number, locate the well within the section. The first letter denotes the 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract as shown in figure 3. The letters are assigned in a counterclockwise direction beginning in the northeast quarter. Within one 10-acre tract, successive well numbers, beginning with 1, are added as suffixes. Figure 3 illustrates the method of numbering a test hole or well. The number 124.48.4ABD indicates the first test hole or well located in the $SE^{1}/4$ of the $NW^{1}/4$ of the $NE^{1}/4$ of section 4, township 124 N., range 48 W.

Test holes were also numbered in the order in which they were drilled. For readability and convenience, these sequential project numbers (for example, BS-3) are used in addition to township-range coordinates.

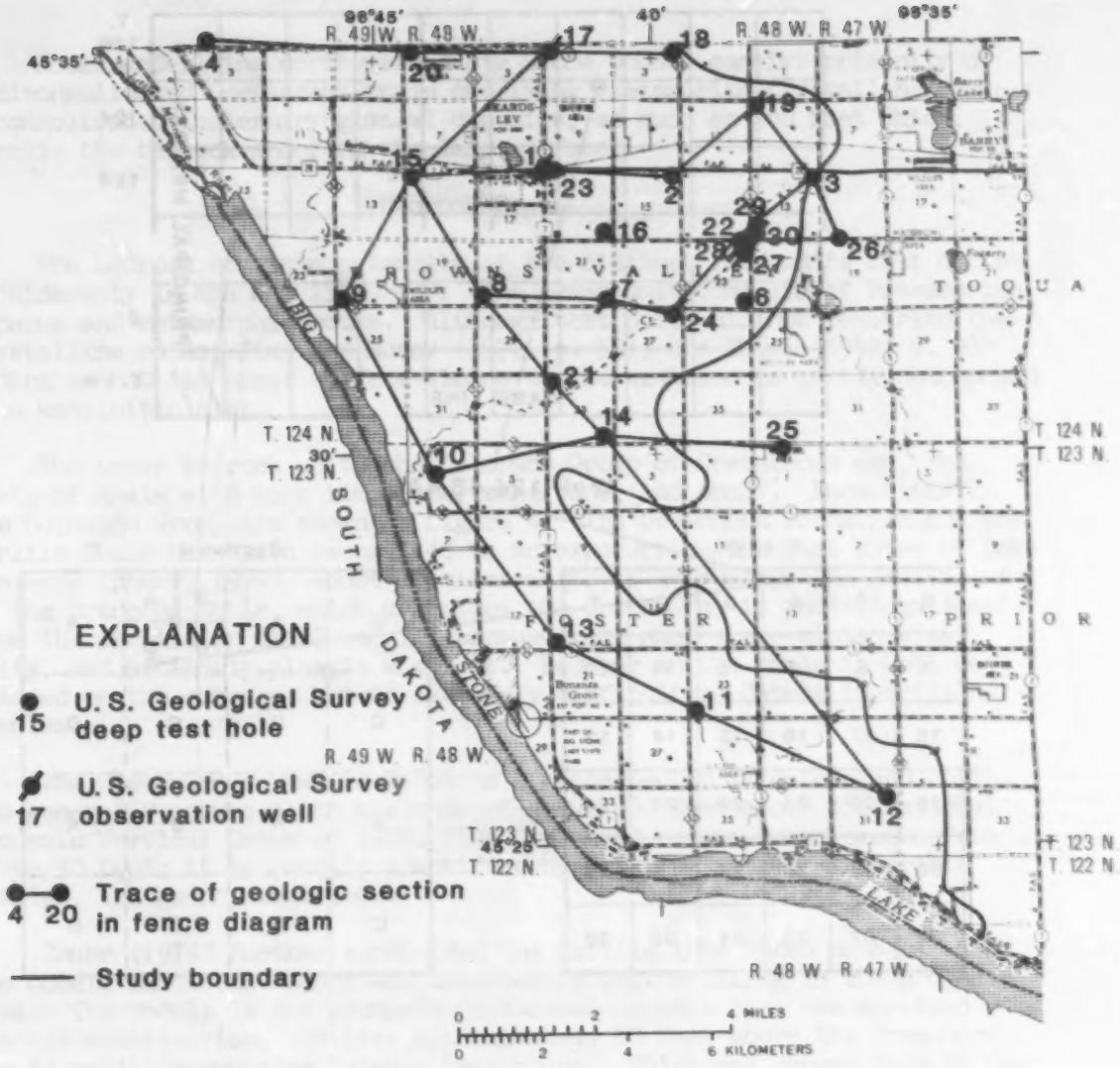


Figure 2.--Location of deep test holes, observation wells, and trace of geologic sections

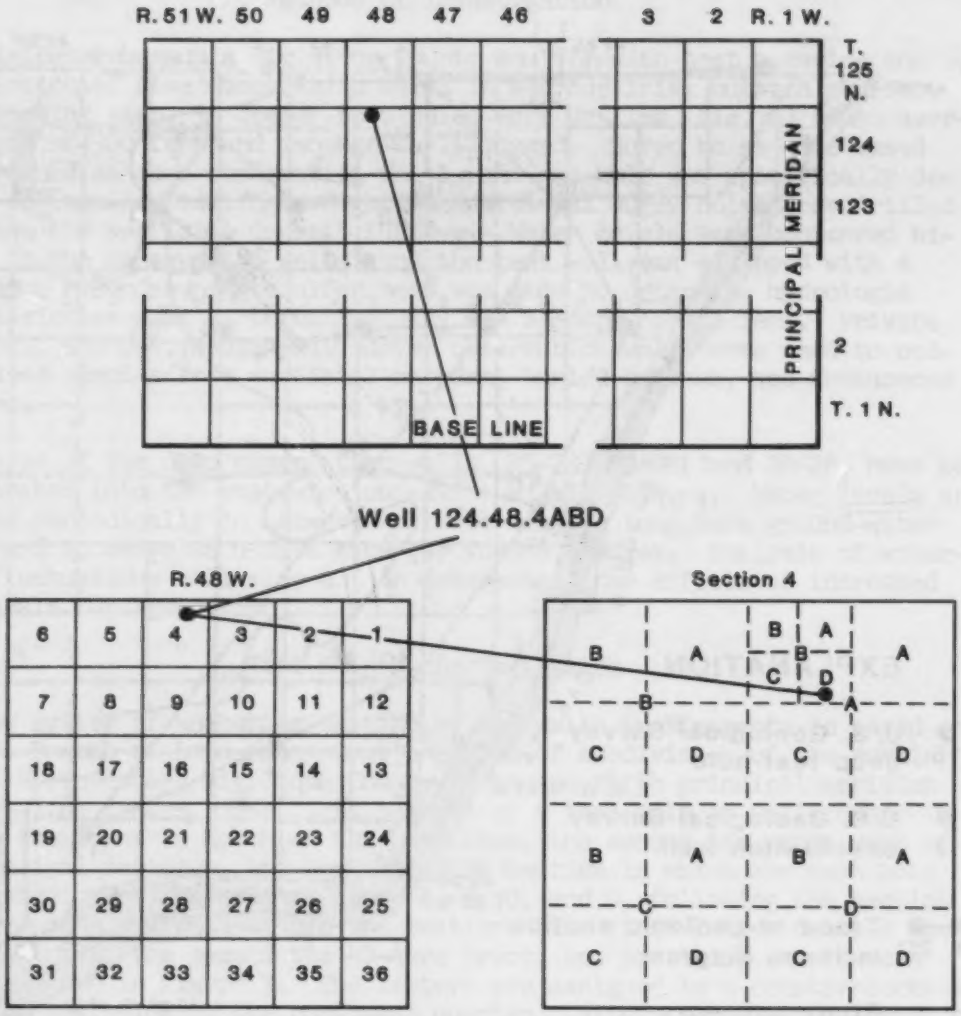


Figure 3.--Test-hole numbering system

GEOLOGY

Rocks underlying northwestern Big Stone County consist primarily of semiconsolidated Cretaceous shale overlying Precambrian crystalline rocks. Unconsolidated Quaternary glacial deposits, as much as 300 feet thick, overlie the bedrock and form the land surface.

Bedrock Deposits

The bedrock consists primarily of two distinct rock units that differ considerably in age and lithology. The lower unit consists of Precambrian igneous and metamorphic rocks. Although test holes did not penetrate the crystalline rocks, Sims and Morey (1972, p. 551) and Thiel (1944, p. 98) indicate that its upper surface slopes to the west and is partly decomposed to a kaolinitic clay.

The upper bedrock unit, the Colorado Group of Cretaceous age, consists of shale with some limestone, sandstone, and chalk. Formations in the Colorado Group are shown in figure 4. The Greenhorn Formation and the Carlile Shale have been recognized in an exposure on the east shore of Lake Traverse (Shurr, 1979), about 10 miles north of Beardsley. An equivalent of the Graneros Shale, which underlies the Greenhorn, is indistinguishable from the Carlile in drill samples because both shales are bluish gray, silty, and extremely plastic when wet. Bedding in the shale is well developed on the outcrop, but is extremely difficult to detect in drilling samples.

The Greenhorn Formation consists of interbedded limestone and chalk and generally occurs at an altitude of about 800 feet above the National Geodetic Vertical Datum of 1929. The Greenhorn ranges in thickness from 20 to 30 feet; it is readily identified by drilling action, lithologic samples, and geophysical logs.

Shurr (1979) further subdivided the Carlile into three members; only the Codell Sandstone Member was detected by test drilling in the project area. The Codell is the youngest Cretaceous deposit that has survived glacial modification. It lies approximately 80 feet above the Greenhorn and is easily correlated between test holes. Thickness ranges from 15 feet in most holes to only 5 feet in test hole BS-14. The deposit consists of very fine, uniform quartz sand with some intermittent clay lenses.

The Greenhorn Formation and Codell Sandstone Member of the Carlile are identifiable on geophysical logs and, hence, have been correlated over much of the study area. Figure 5 shows geophysical and geologic logs of test hole BS-15, which best typify the Cretaceous bedrock.

In some locations, glacial meltwater streams eroded channels into the bedrock. These channels then filled with sand, resulting in the stratigraphic relationship shown in figure 6. The sand-filled channel in the vicinity of test hole BS-22 forms a buried-outwash aquifer.

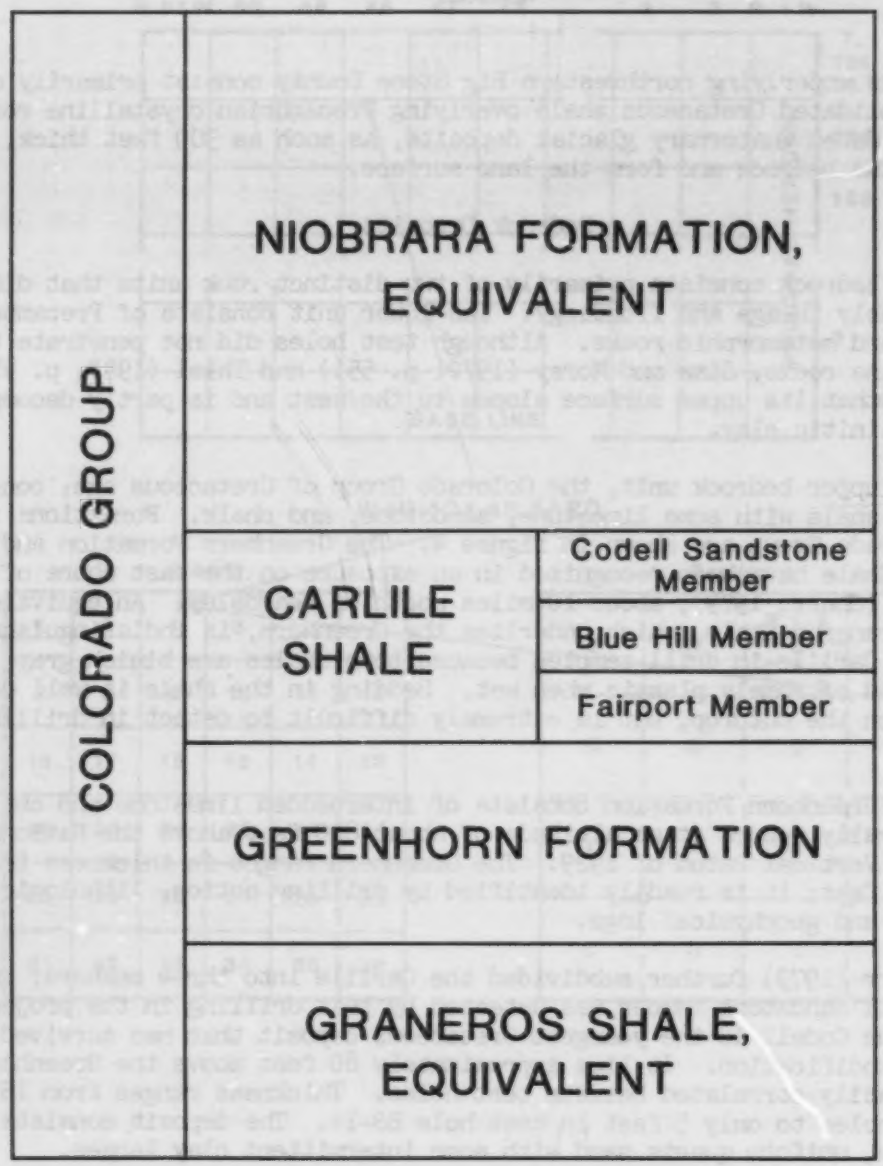


Figure 4.--Correlation of bedrock units in the Upper Cretaceous Series in southwestern Minnesota (modified from Austin, 1972)

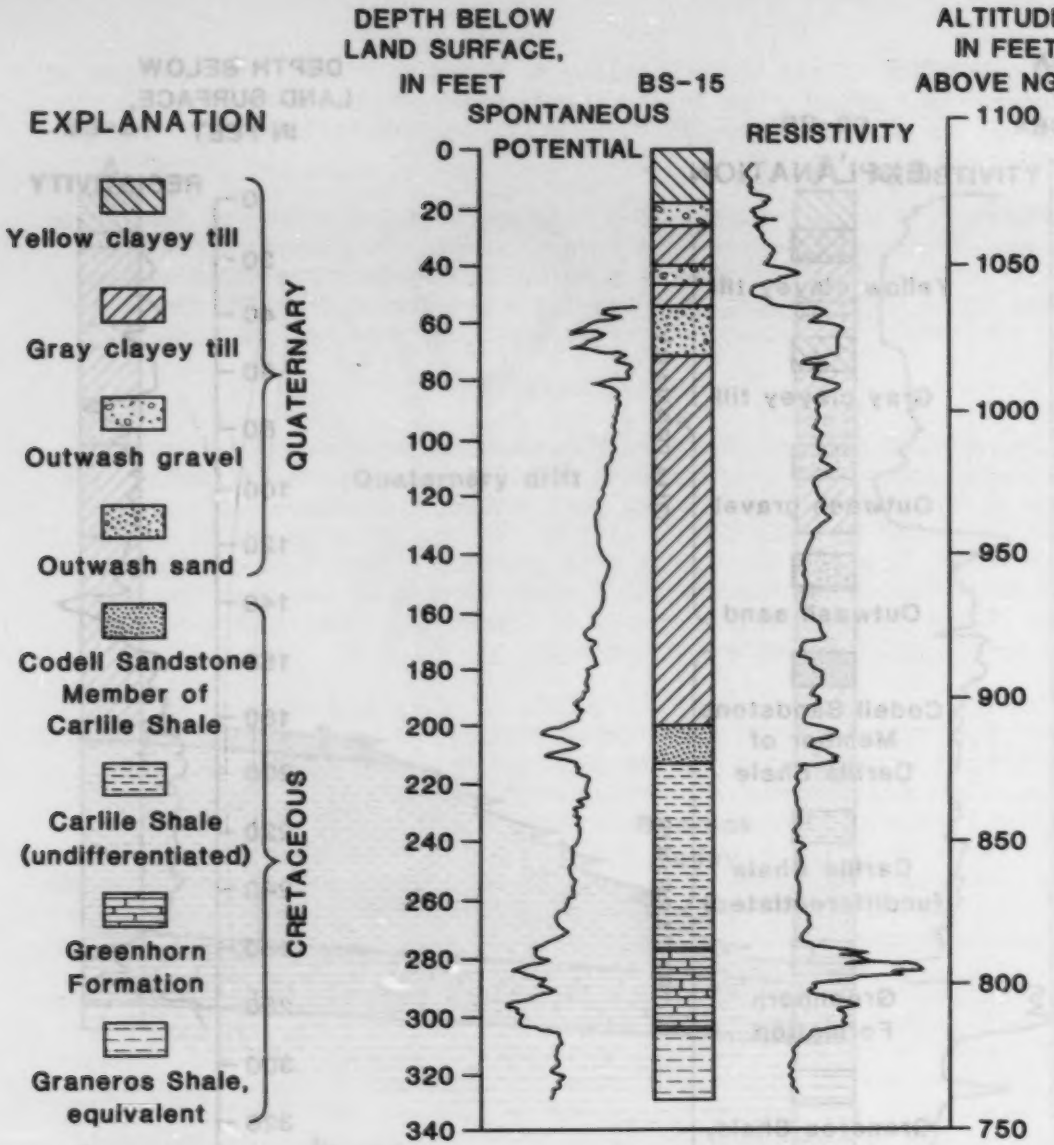


Figure 5.--Log of test hole BS-15, typical of Cretaceous rocks overlain by drift

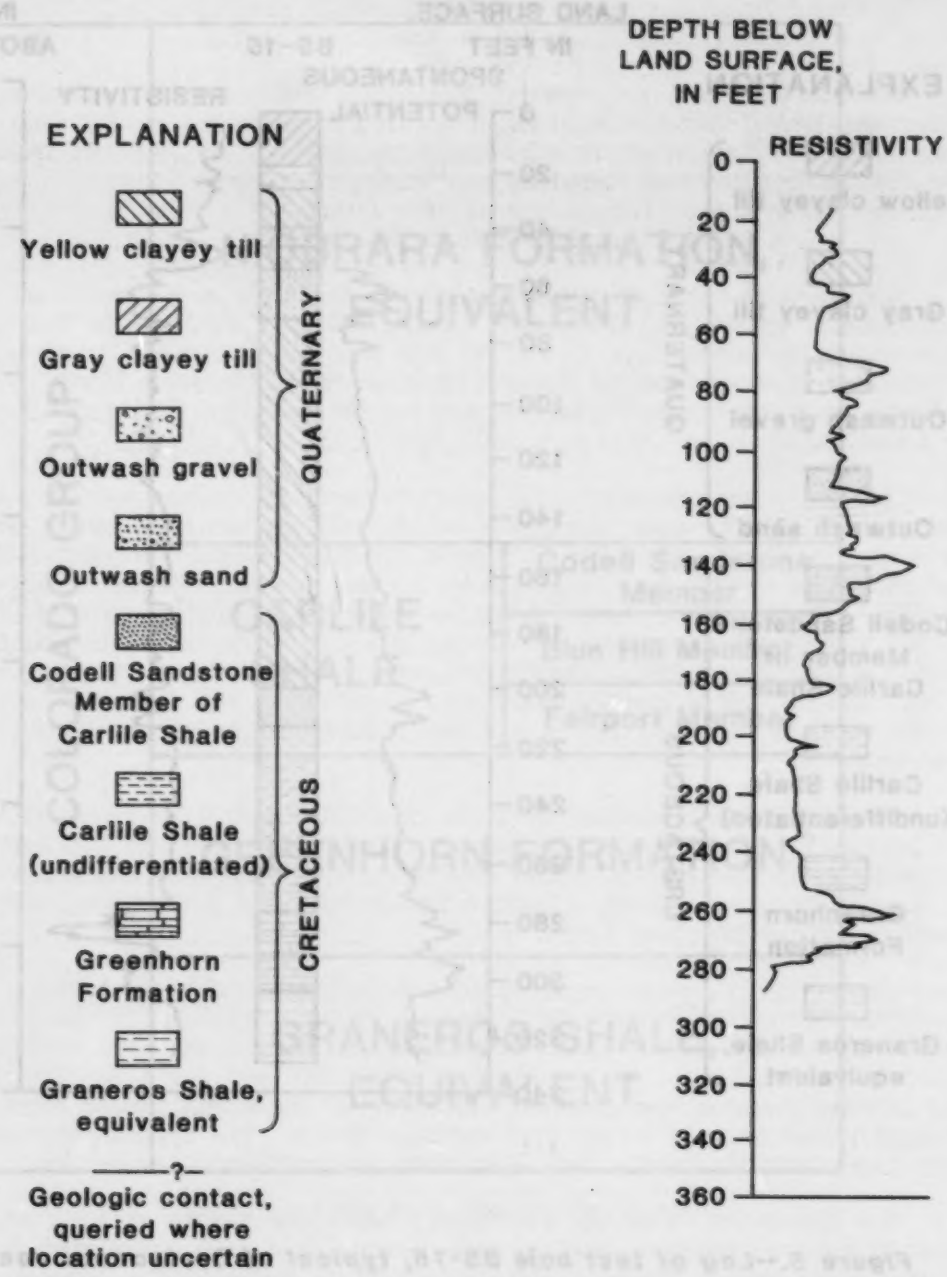
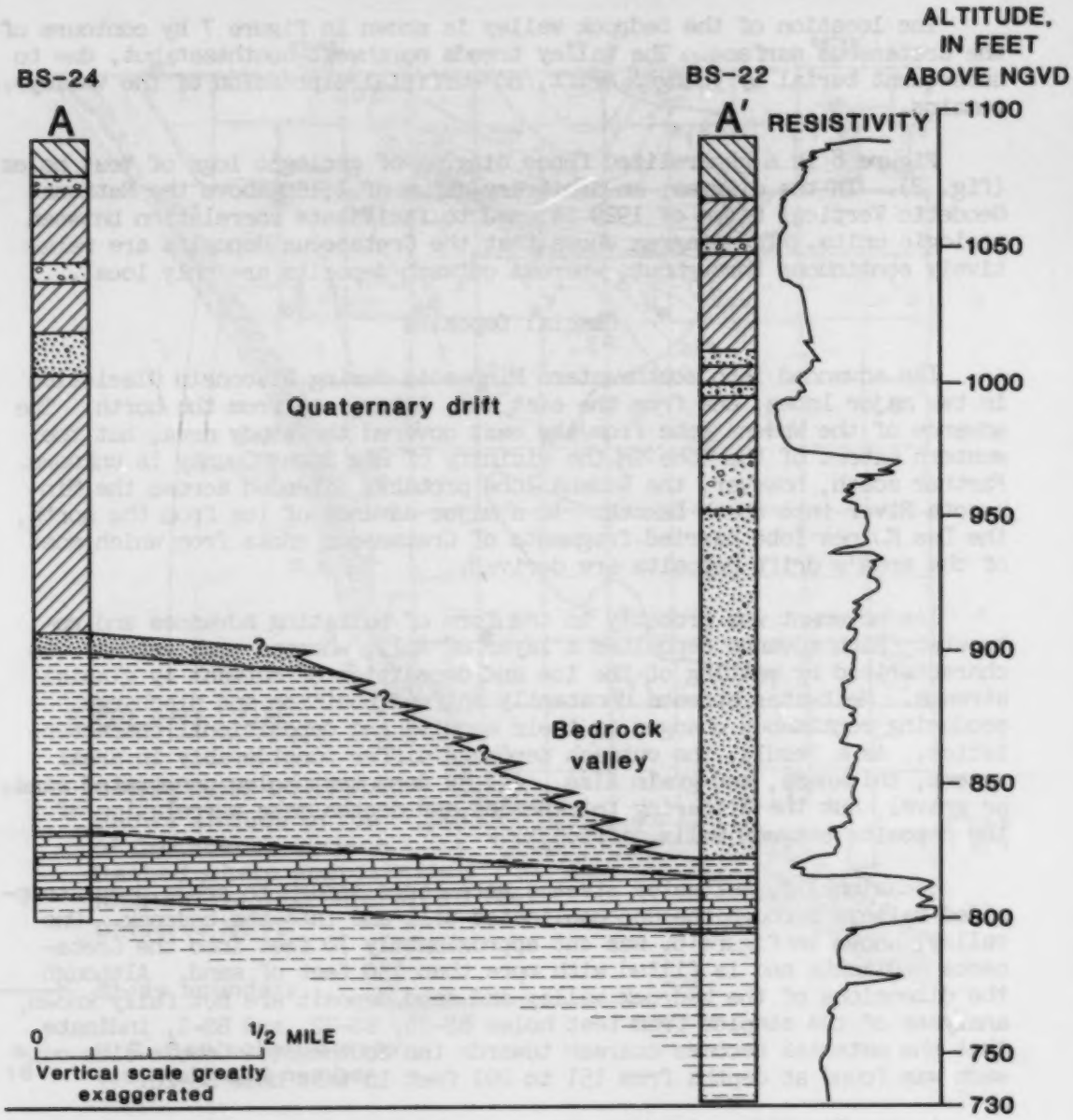


Figure 6.--Geologic section A-A' showing the stratigraphic relationships



associated with buried aquifers, and logs of test holes BS-24 and BS-22

The location of the bedrock valley is shown in figure 7 by contours of the Cretaceous surface. The valley trends northwest-southeast but, due to subsequent burial by younger drift, no surficial expression of the valley remains.

Figure 8 is a generalized fence diagram of geologic logs of test holes (fig. 2). In the diagram, an arbitrary datum of 1,100 above the National Geodetic Vertical Datum of 1929 is used to facilitate correlation between geologic units. The diagram shows that the Cretaceous deposits are relatively continuous throughout, whereas outwash deposits are only local.

Glacial Deposits

Ice advanced into southwestern Minnesota during Wisconsin Glaciation in two major lobes; one from the east and, later, one from the north. The advance of the Wadena lobe from the east covered the study area, but the western extent of the lobe in the vicinity of Big Stone County is unknown. Farther south, however, the Wadena lobe probably extended across the Minnesota River into South Dakota. In a major advance of ice from the north, the Des Moines lobe carried fragments of Cretaceous rocks from which most of the area's drift deposits are derived.

Ice movement was probably in the form of pulsating advances and retreats. Each advance deposited a layer of till, whereas each retreat was characterized by melting of the ice and deposition of outwash by glacial streams. Meltwater streams constantly shifted position and discharge, producing continuous changes in their erosive and depositional characteristics. As a result, the outwash deposits differ considerably in areal extent, thickness, and grain size. All 30 deep test holes penetrated sand or gravel, but the differing thicknesses and depths make correlation of the deposits between wells difficult.

Occasionally, meltwater streams were large enough to erode deep steep-sided valleys through the unconsolidated till and into the bedrock. One valley, shown in figure 6, was cut approximately 70 feet into the Cretaceous sediments and is filled with more than 130 feet of sand. Although the dimensions of the bedrock valley and sand deposit are not fully known, analyses of the samples from test holes BS-26, BS-22, and BS-1, indicate that the material becomes coarser towards the southeast. Cobble-size outwash was found at depths from 151 to 201 feet in test hole BS-26.

As the Des Moines lobe finally retreated, it deposited the Big Stone recessional moraine, which impounded drainage and ultimately formed glacial Lake Agassiz to the north (Leverett, 1932). At about the same time, a much smaller recessional moraine formed northeast of Beardsley (fig. 9) and is represented by a 25 to 30 foot rise in the topography. Surficial outwash sand and gravel was deposited when water from the melting ice flowed across the moraine (fig. 9).

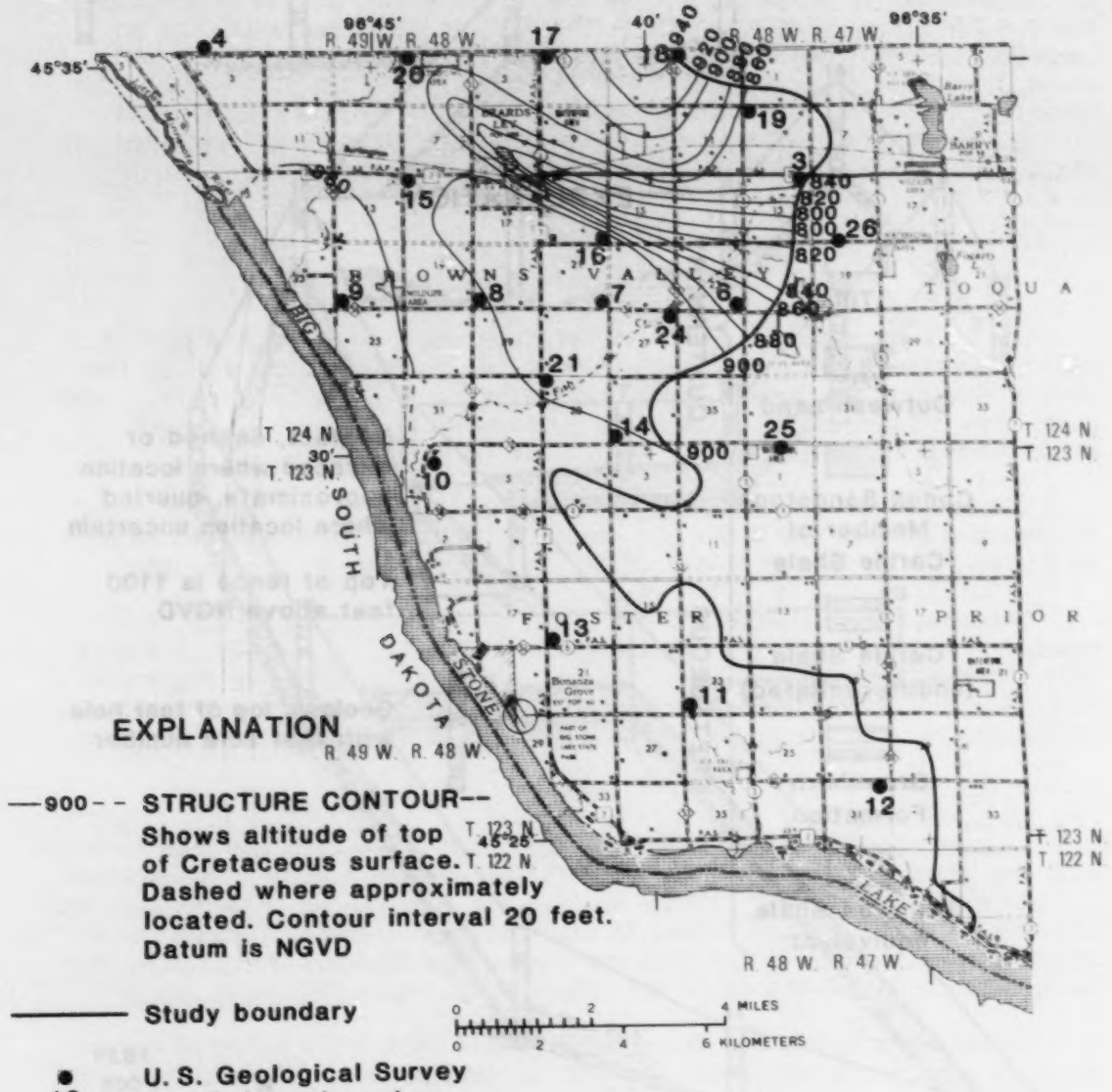


Figure 7.--Contours of the Cretaceous surface

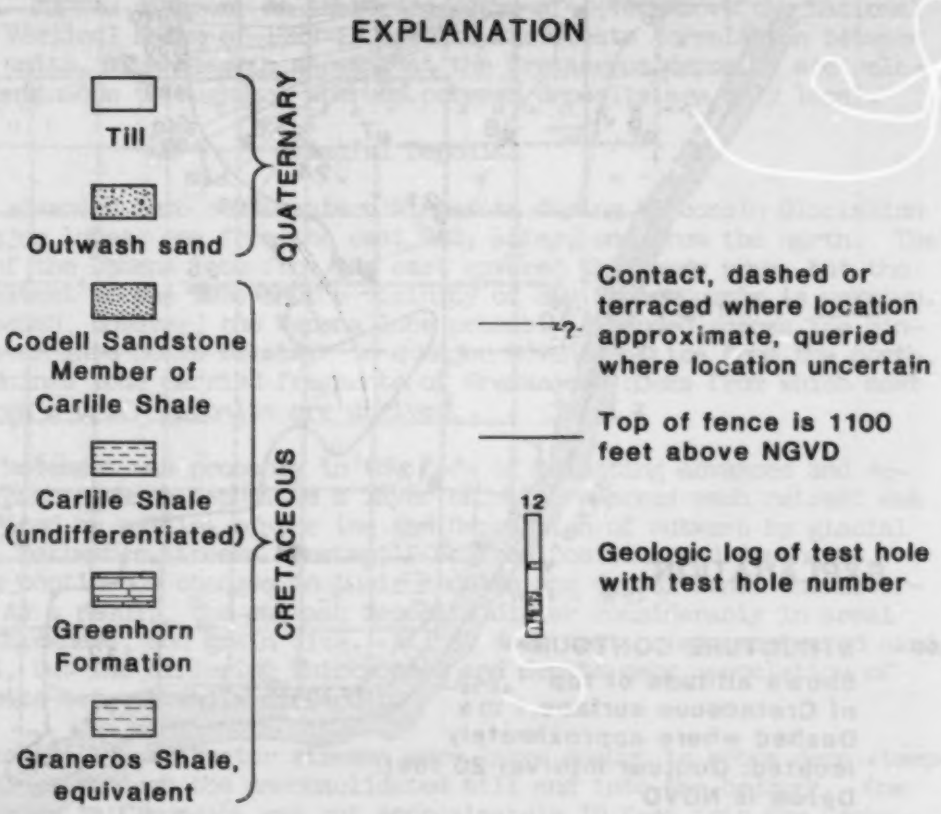
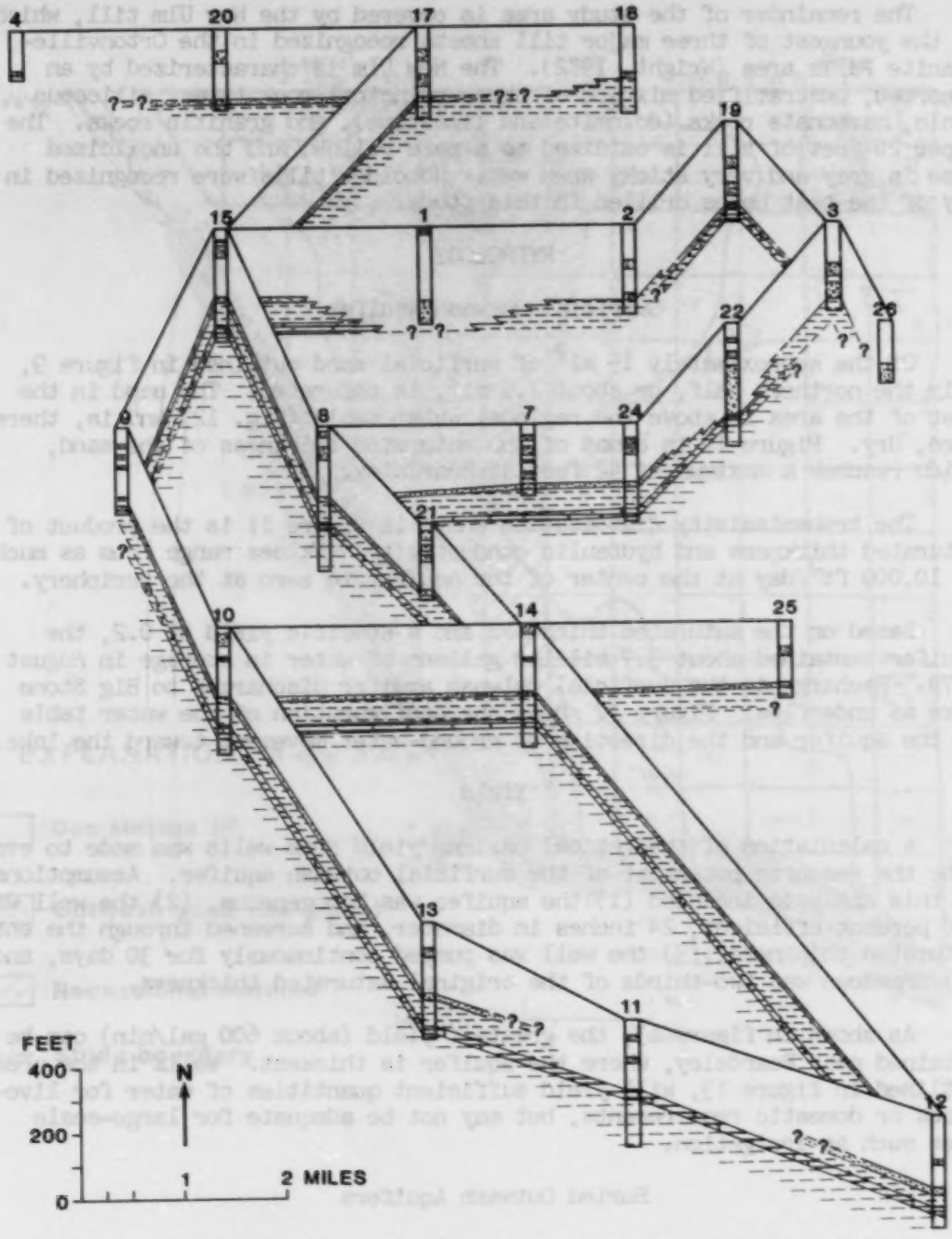


Figure 8.--Generalized fence diagram of



northwestern Big Stone County, Minnesota

The remainder of the study area is covered by the New Ulm till, which is the youngest of three major till sheets recognized in the Ortonville-Granite Falls area (Wright, 1972). The New Ulm is characterized by an unsorted, unstratified mixture of three principal rock types, siliceous shale, carbonate rocks (dolomite and limestone), and granitic rocks. The upper 20 feet of till is oxidized to a pale yellow; and the unoxidized base is gray and very sticky when wet. No older tills were recognized in any of the test holes drilled in this study.

HYDROLOGY

Surficial Outwash Aquifer

Of the approximately 15 mi^2 of surficial sand outlined in figure 9, only the northern half, or about 7.5 mi^2, is saturated. The sand in the rest of the area is above the regional water table (fig. 12) and is, therefore, dry. Figure 10 is a map of the saturated thickness of the sand, which reaches a maximum of 42 feet at Beardsley.

The transmissivity distribution shown in figure 11 is the product of saturated thickness and hydraulic conductivity. Values range from as much as 10,000 ft^2/day at the center of the aquifer to zero at the periphery.

Based on the saturated thickness and a specific yield of 0.2, the aquifer contained about 3.7 billion gallons of water in storage in August 1979. Recharge to the surficial outwash aquifer discharges to Big Stone Lake as underflow. Figure 12 shows the configuration of the water table in the aquifer and the direction of ground-water movement toward the lake.

Yield

A calculation of theoretical maximum yield from wells was made to evaluate the resource potential of the surficial outwash aquifer. Assumptions in this analysis included (1) the aquifer was homogeneous, (2) the well was 100 percent efficient, 24 inches in diameter, and screened through the entire saturated thickness, (3) the well was pumped continuously for 30 days, and (4) drawdown was two-thirds of the original saturated thickness.

As shown in figure 13, the greatest yield (about 600 gal/min) can be obtained near Beardsley, where the aquifer is thickest. Wells in the area, outlined in figure 13, will yield sufficient quantities of water for livestock or domestic requirements, but may not be adequate for large-scale uses such as irrigation.

Buried Outwash Aquifers

Buried outwash aquifers are generally discontinuous bodies of sand that are variable in thickness, grain size, and depth below land surface. To define them adequately by test drilling, a grid spacing of half a mile or less would be necessary, which is costly. A statistical approach was used, therefore, to map the generalized distribution of buried outwash.

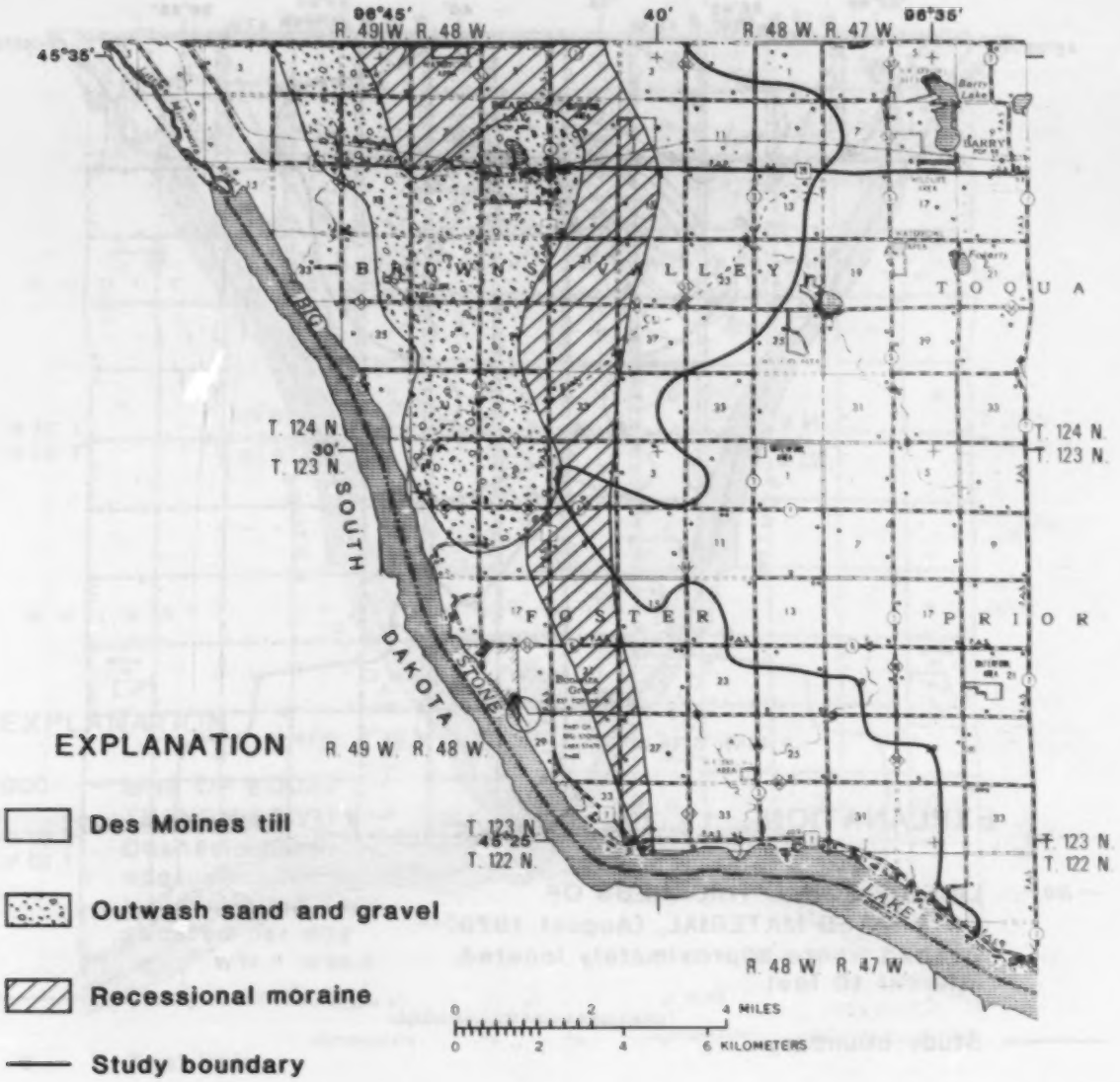


Figure 9.--Generalized surficial geology (modified from Leverett, 1932)

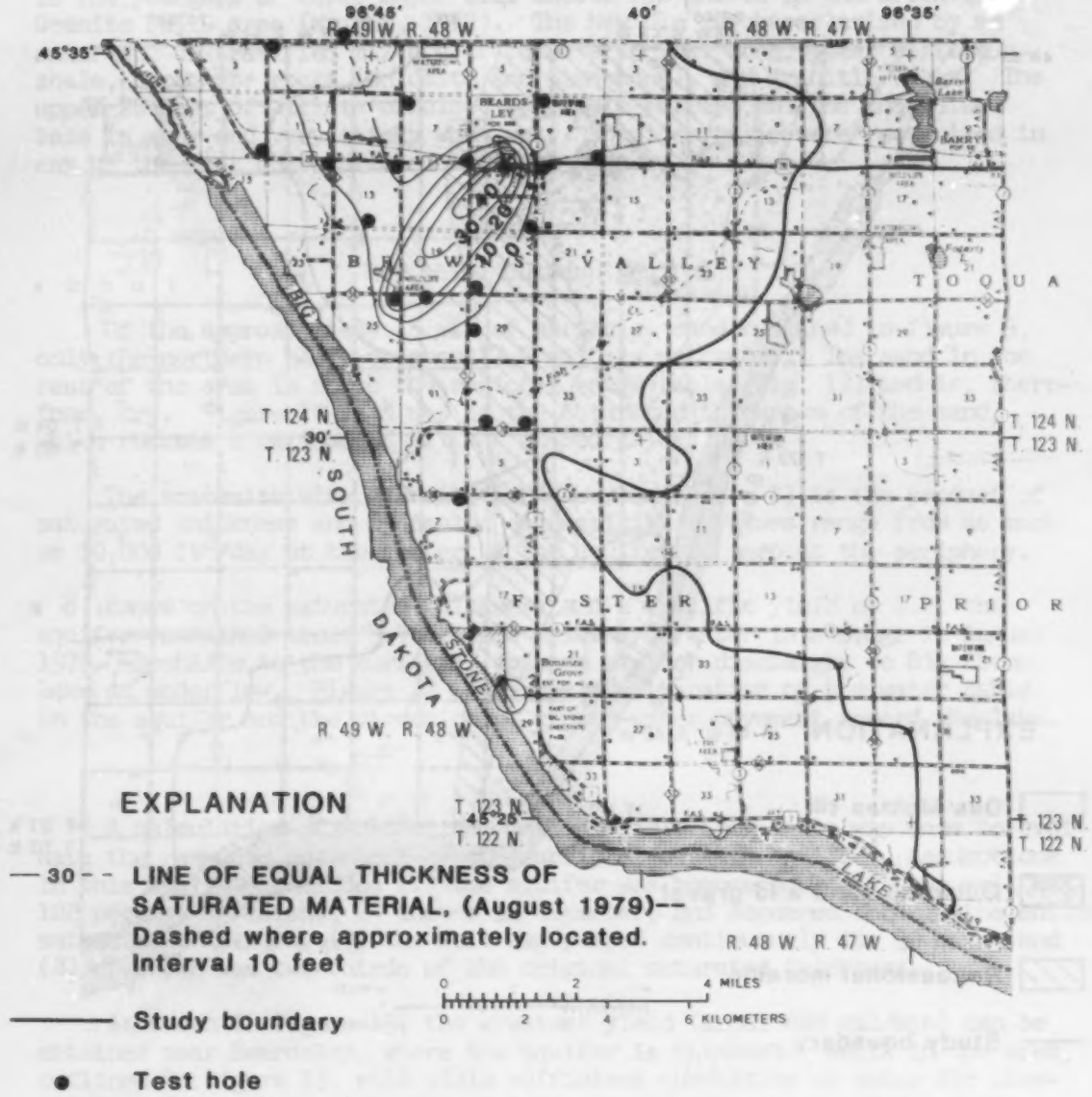


Figure 10.--Saturated thickness of surficial outwash

Figure 11.--Transmissivity of surficial outwash

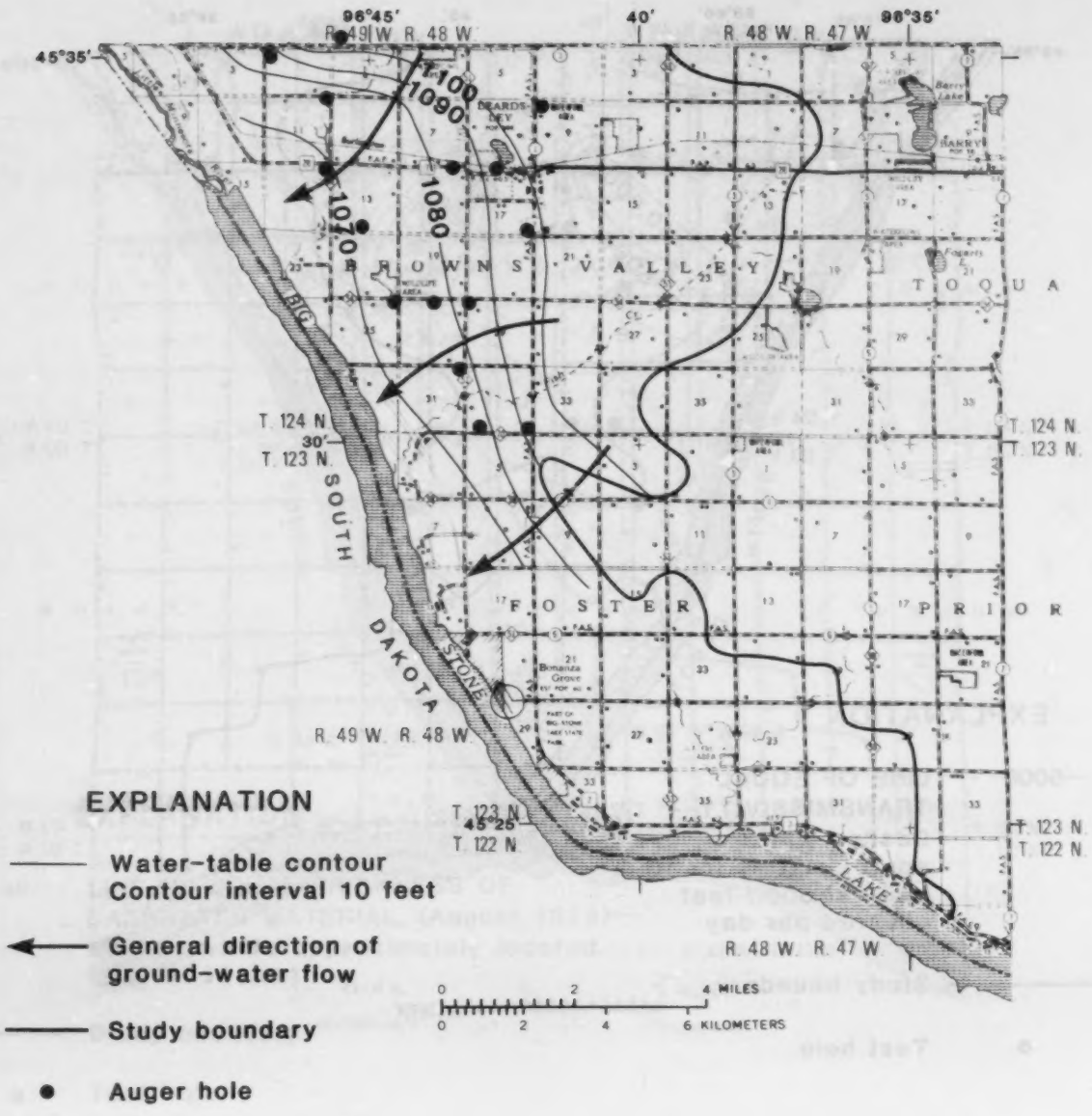


Figure 12.--Water-table configuration in northwestern Big Stone County

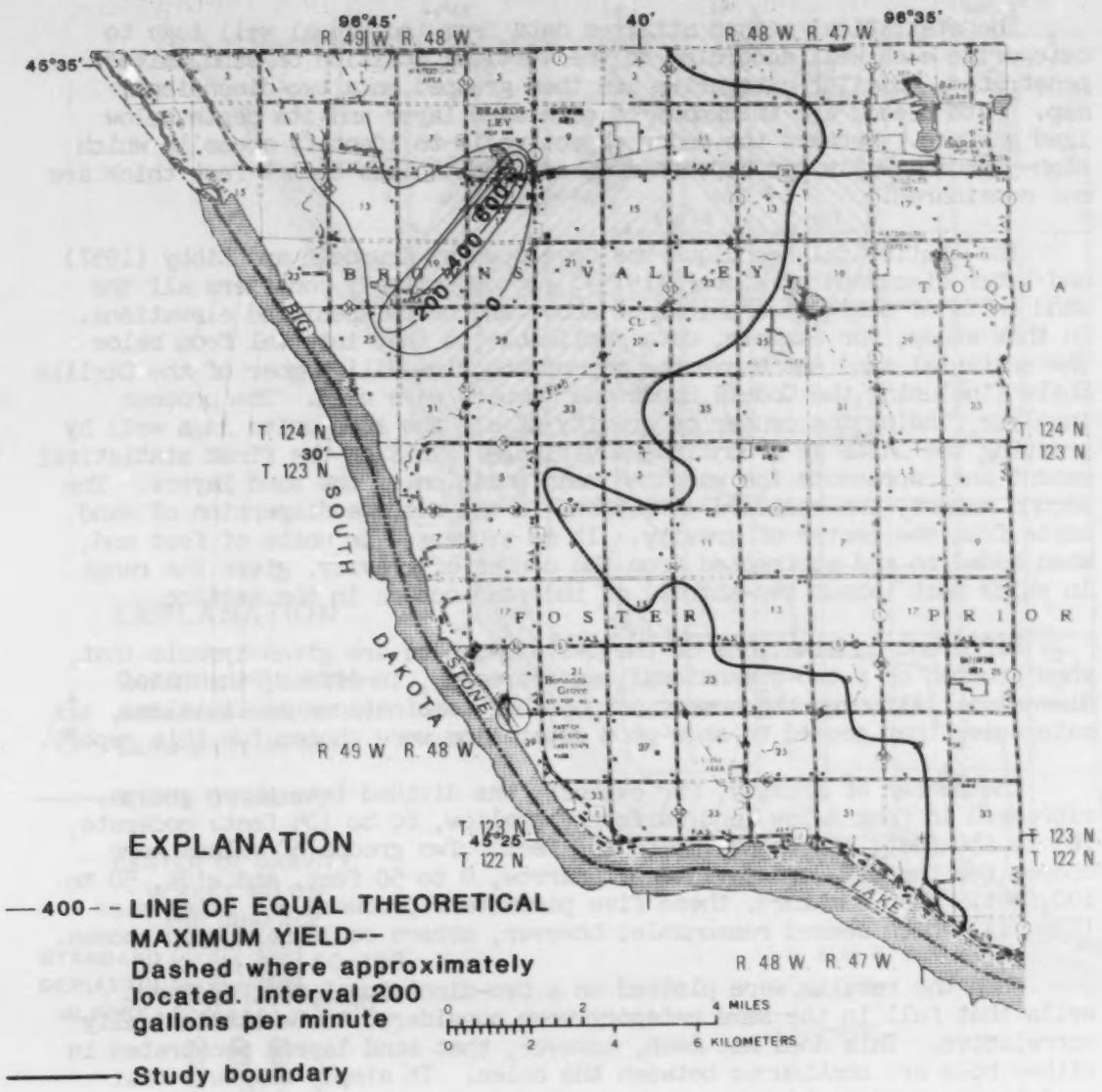


Figure 13.--Theoretical maximum yield of wells in the surficial-outwash aquifer

Statistical method of mapping buried outwash

The statistical method utilizes data from individual well logs to categorize each well according to the vertical position of sand units penetrated. Similar categories are then grouped on a two-dimensional map. Data needed are thickness of each sand layer and its depth below land surface. Because the major objective is to identify areas in which high-yielding wells can be obtained, sand units less than 4 feet thick are not considered.

The statistical technique was developed by Krumbein and Libby (1957) and later discussed by Winter (1975). It objectively considers all the sand units of designated thickness above and below specified elevations. In this study, for example, data applicable to that interval from below the surficial sand and above the top of the Blue Hill Member of the Carlile Shale (including the Codell Sandstone Member) were used. The process involves finding the center of gravity of all the sand units in a well by treating the units as a continuous variable. This is the first statistical moment and represents the weighted mean position of the sand layers. The second moment, the standard deviation, is the average dispersion of sand units from the center of gravity. It is expressed in units of feet and, when added to and subtracted from the center of gravity, gives the range in which most (about two-thirds) of the sand occurs in the section.

Different combinations of the two parameters are given symbols that, when grouped on a two-dimensional map represent, in effect, the third dimension. Although the number of possible combinations is limitless, six categories that seemed to show good separation were chosen for this report.

The center of gravity, for example, was divided into three groups, expressed in feet below land surface: shallow, 60 to 105 feet; moderate, 105 to 150 feet; and deep, 150 to 250 feet. Two groups of values were chosen for the standard deviation: narrow, 0 to 50 feet, and wide, 50 to 100 feet. When combined, these five parameters produced six categories (fig. 14) which seemed reasonable; however, others could have been chosen.

When the results were plotted on a two-dimensional map, adjacent wells that fell in the same category were considered to be statistically correlative. This does not mean, however, that sand layers penetrated in either hole are continuous between the holes. It simply suggests that sand layers tend to be more numerous at the same general depth below land surface and, therefore, represent the optimum depth or range of depths in which one should expect to find water.

Figure 14 shows two major groups of wells with similar statistical results. The group southwest of Beardsley has a shallow center of gravity, but a wide dispersion. Its outline coincides with the surficial deposit and indicates an area be susceptible to the more recent outwash. This area is, therefore, ideal for a domestic or stock water supply. Because of the wide dispersion, however, vertical connection between layers would be reduced. This, combined with a small available drawdown in most aquifers, would not likely support the yield necessary for an irrigation well.

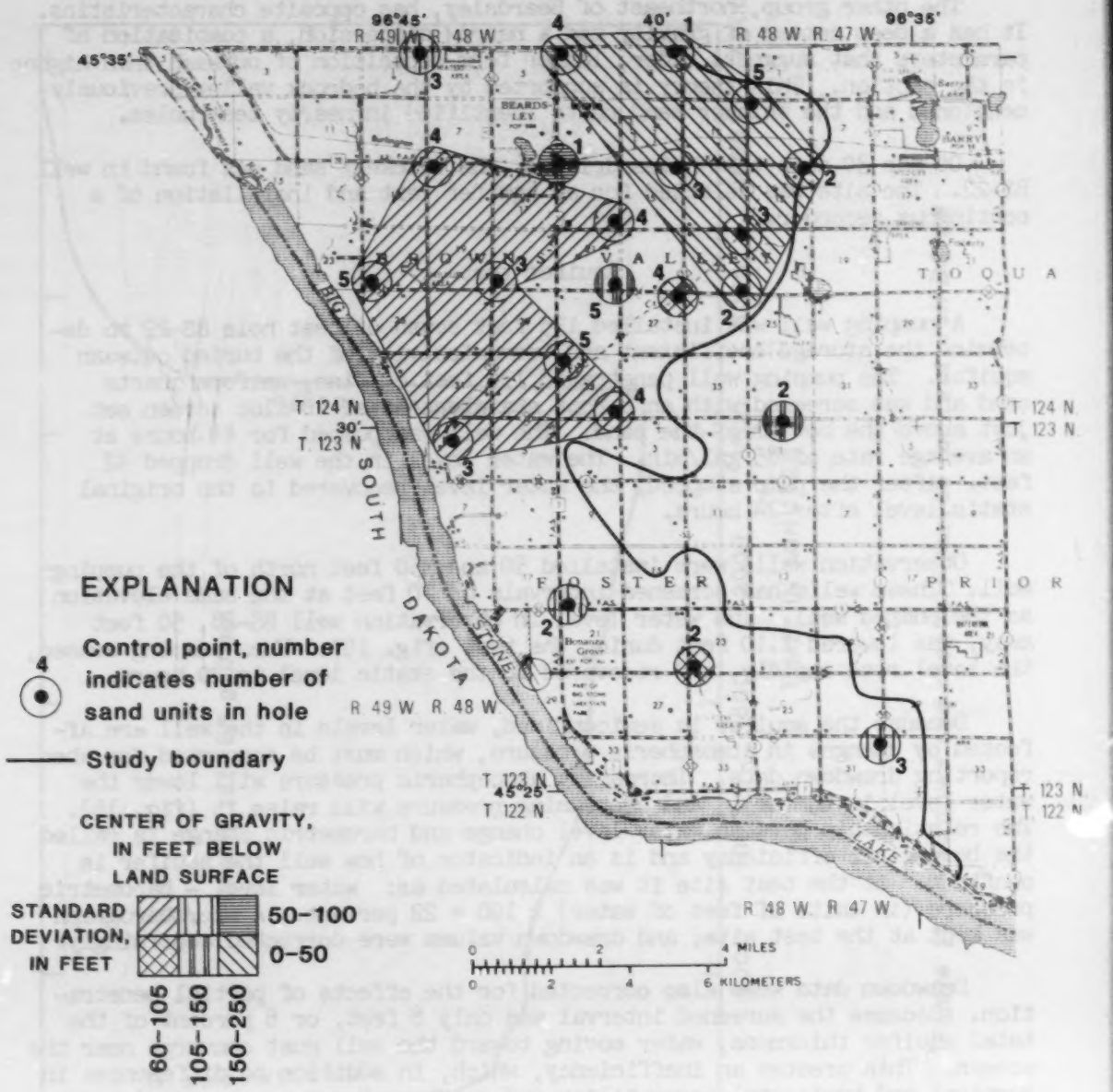


Figure 14.--Statistical distribution of sand units in drift, 4 or more feet thick

The other group, northeast of Beardsley, has opposite characteristics. It has a deep center of gravity and a narrow dispersion, a combination of parameters that suggests older, longer term deposition of outwash than higher in the section. This theory is supported by the bedrock valley previously mentioned and the thicker sand units identified in nearby test holes.

Of the 30 deep test holes drilled, the thickest sand was found in well BS-22. The site was selected for an aquifer test and installation of a continuous recorder.

Aquifer test

A pumping well was installed 135 feet south of test hole BS-22 to determine the storage coefficient and transmissivity of the buried outwash aquifer. The pumping well penetrated 130 feet of fine, uniform quartz sand and was screened with an 8-foot stainless-steel 10-slot screen set just above the bottom of the sand. The well was pumped for 44 hours at an average rate of 85 gal/min. The water level in the well dropped 42 feet. After the pump stopped, the water level recovered to the original static level after 24 hours.

Observation wells were installed 50 and 350 feet north of the pumping well. These wells had screened intervals of 20 feet at the same elevation as the pumped well. The water level in observation well BS-28, 50 feet away, was lowered 1.10 feet during the test (fig. 15). When pumping ceased, the level rose rapidly, and recovered to the static level in 20 hours.

Because the aquifer is semiconfined, water levels in the well are affected by changes in atmospheric pressure, which must be accounted for when reporting drawdown data. Increasing atmospheric pressure will lower the water level in the well, and decreasing pressure will raise it (fig. 16). The relationship between water-level change and barometric change is called the barometric efficiency and is an indicator of how well the aquifer is confined. At the test site it was calculated as: water level - barometric pressure (in units of feet of water) x 100 = 22 percent. A microbarograph was kept at the test site, and drawdown values were corrected accordingly.

Drawdown data were also corrected for the effects of partial penetration. Because the screened interval was only 8 feet, or 6 percent of the total aquifer thickness, water moving toward the well must converge near the screen. This creates an inefficiency, which, in addition to differences in vertical and horizontal permeability and entrance losses, accounts for about 95 percent of the total 42 feet of drawdown. Increasing the screen length, however, is expensive and may not be necessary if available drawdown is sufficient for the desired yield.

The aquifer-test data were analyzed by the Theis nonequilibrium formula, the distance-drawdown and time-drawdown methods, and the Theis recovery method. Hydraulic conductivity determined by these methods ranged from 83 to 103 ft/day, respectively. The values are representative of a fine sand on the Wentworth scale and are in agreement with sieve analyses. The storage coefficient ranged from 0.0001 to 0.002.

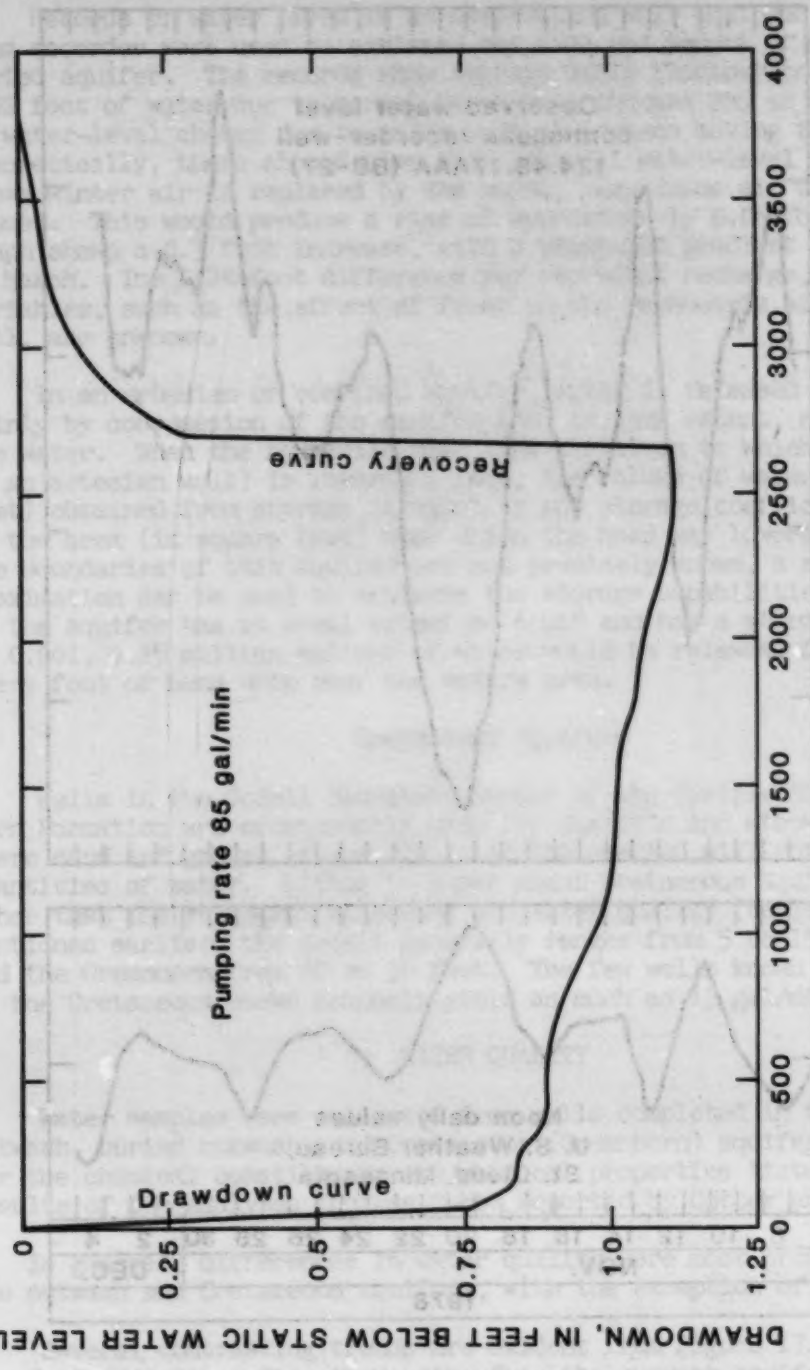


Figure 15.--Drawdown and recovery curves for test well BS-28

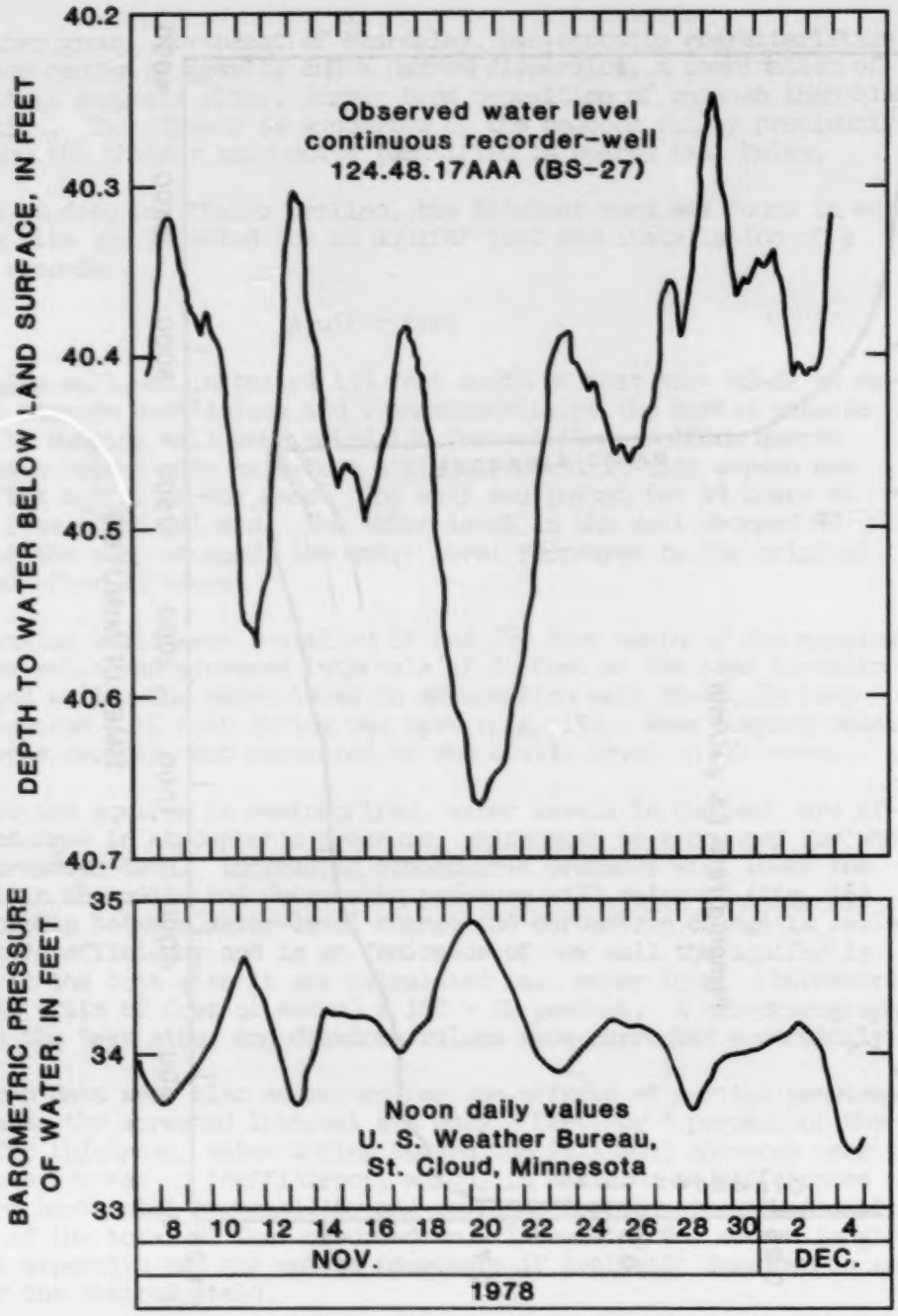


Figure 16.--Diagram comparing barometric changes to water-level changes in the buried outwash aquifer

Records of water level in an observation well equipped with a continuous recorder were used to estimate the time and amount of recharge to the buried aquifer. The records show average daily fluctuations of 0.01 to 0.02 foot of water due to normal barometric changes and as much as 0.3 foot of water-level change due to major weather systems moving through the area. Theoretically, there should also be a seasonal water-level change when dry, heavy winter air is replaced by the moist, less-dense air of spring and summer. This would produce a rise of approximately 0.06 foot. The hydrograph shows a 0.3 foot increase, with a steepened gradient near the end of March. The 0.24-foot difference may represent recharge, although some variables, such as the effect of frost on the barometric efficiency of the well, are unknown.

In an artesian or confined aquifer, water is released from storage mainly by compression of the aquifer and, to some extent, expansion of the water. When the hydraulic head (the elevation to which water rises in an artesian well) is lowered 1 foot, the volume of water (in cubic feet) obtained from storage is equal to the storage coefficient multiplied by the area (in square feet) over which the head was lowered. Although the boundaries of this aquifer are not precisely known, a reasonable approximation can be used to estimate the storage capabilities. For example, if the aquifer has an areal extent of 6 mi^2 and has a storage coefficient of 0.001, 1.25 million gallons of water would be released from storage for every foot of head drop over the entire area.

Cretaceous Aquifers

Wells in the Codell Sandstone Member of the Carlile Shale and the Greenhorn Formation are occasionally used for domestic and stock water supplies where sand and gravel layers higher in the section will not yield sufficient quantities of water. Little is known about Cretaceous aquifers, however, other than their general thickness and water quality (tables 1 and 2). As mentioned earlier, the Codell generally ranges from 5 to 15 feet in thickness and the Greenhorn from 20 to 30 feet. The few wells known to be completed in the Cretaceous rocks commonly yield as much as 15 gal/min.

WATER QUALITY

Water samples were collected from wells completed in the surficial outwash, buried outwash, and Cretaceous (Greenhorn) aquifers and analyzed for the chemical constituents and physical properties listed in table 1. Results of the analyses include those reported by Cotter and others (1966).

In general, differences in water quality were most pronounced between the outwash and Cretaceous aquifers, with the exception of nitrate.

Several contrasting trends are evident from figure 17. Water from the Cretaceous is softer than water from the outwash aquifers, yet has higher concentrations of sodium and boron. Nitrate concentrations are considerably higher in the surficial aquifer.

Table 1.--Chemical analyses of water from surficial outwash, buried outwash, and Cretaceous aquifers

[Results in milligrams per liter except as stated]

	Surficial outwash			Buried outwash			Cretaceous aquifer		
	121.46. 16CBB	124.48.[a] 17BAB	119.44. 29ABA	118.42. 6AAC	124.48.[a] 23AAA	123.46. 16DBD	124.49. 4CDC	119.46. 35DAA	Minimum[b] standards
Depth of well (ft).....	71	91	16	140	221	335	400	293	---
Silica, dissolved (SiO_2)...	31	30	28	23	29	29	8.8	6.3	---
Boron, total (B).....	0.26	0.05	0.21	0.53	0.20	0.86	4.0	4.3	0.5
Iron, total (Fe).....	2.5	0.05	0.05	13	2.5	1.9	2.2	5.0	0.3
Manganese, total (Mn).....	0.24	0.01	0.68	0.16	0.52	0.09	0	0.06	0.05
Calcium, dissolved (Ca)....	171	84	369	322	160	92	21	37	---
Magnesium, dissolved (Mg)..	76	38	272	167	43	50	15	11	---
Sodium, dissolved (Na).....	47	6.9	83	58	40	206	1230	1170	---
Potassium, dissolved (K)...	11	3.4	11	10	7.5	5.5	8.2	11	---
Sulfate, dissolved (SO_4)...	244	41	1400	1160	380	482	1330	1300	250
Chloride, dissolved (Cl)...	32	28	86	1.0	2.9	26	704	705	250
Fluoride, dissolved (F)....	0.2	0.2	0.3	0.4	0.2	0.6	5.2	2.9	1.5
Nitrate, total (NO_3).....	20	30	205	0.3	0.09	5.4	12	0.3	44
Dissolved solids residue on evaporation at 180°C..	973	427	2930	2140	946	1150	3630	3470	500
Alkalinity (as $CaCO_3$).....	---	280	---	---	300	---	---	---	---
Hardness, total.....	741	370	2040	1490	580	434	113	139	---
Hardness, noncarbonate.....	218	86	1560	1080	280	75	0	0	---
Specific conductance, micromhos per cm at 25°C.	1430	730	3170	2400	1180	1620	5360	5240	---
pH.....	7.9	7.6	7.8	7.7	7.6	7.8	8.0	8.1	---
Sodium-adsorption ratio....	0.7	0.2	0.8	0.7	0.7	4.3	50	43	---

[a]Sample collected June 20, 1979 (other samples from Cotter and others, 1966).

[b]Recommended limits for domestic consumption (Minnesota Pollution Control Agency, 1972).

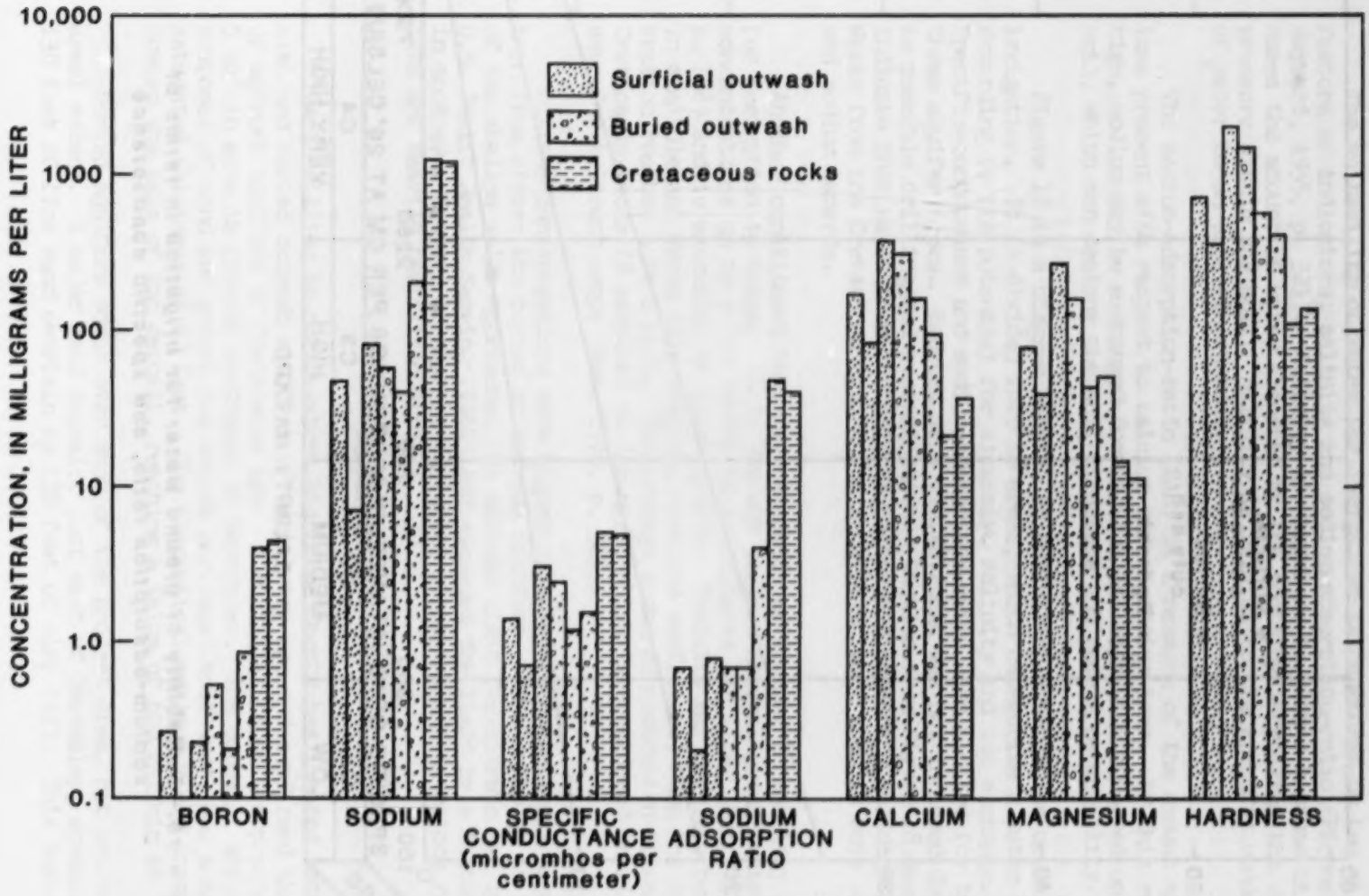


Figure 17.--Comparison of water-quality data from eight samples in surficial outwash, buried outwash and Cretaceous aquifers

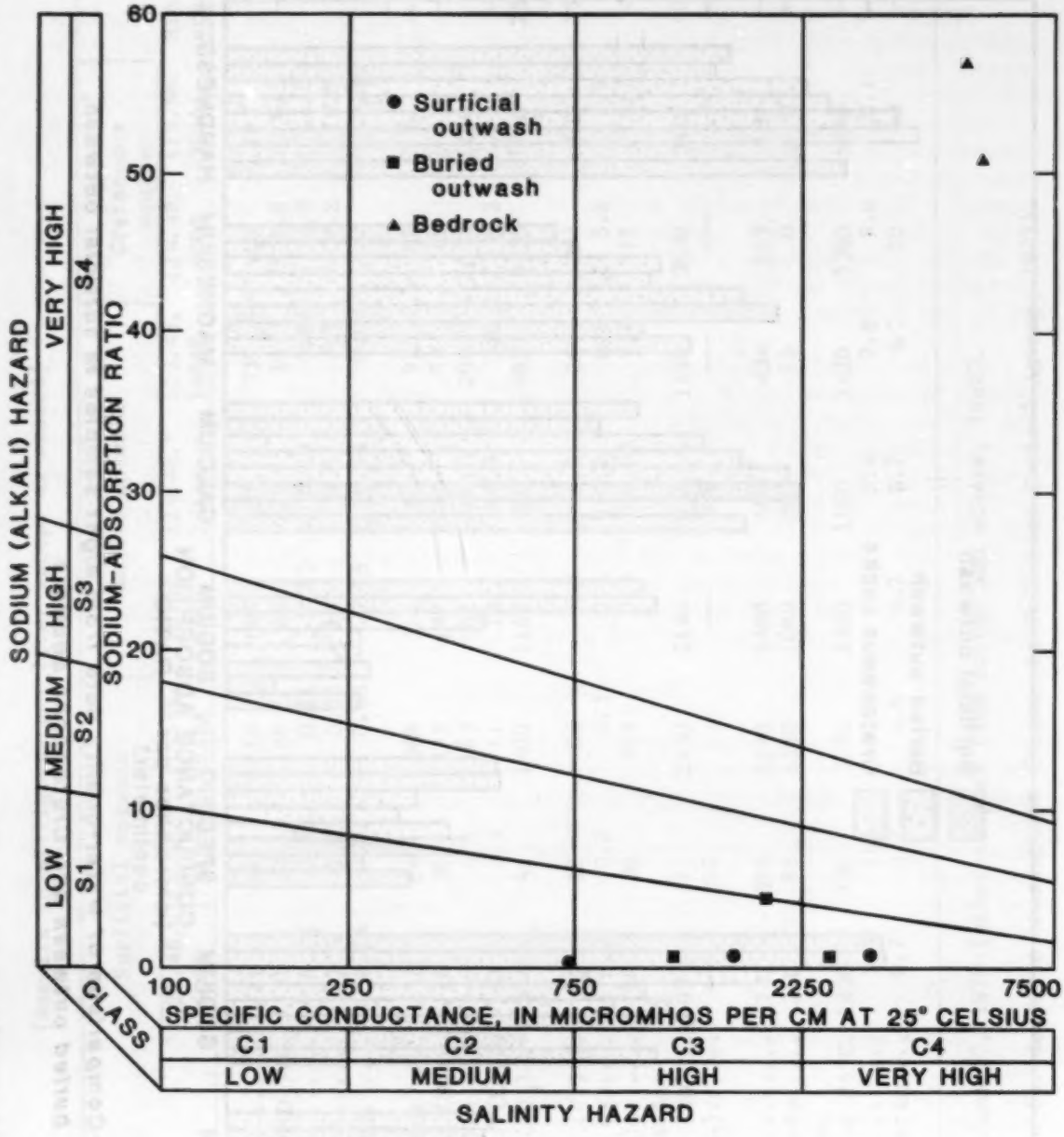


Figure 18.--Suitability of ground water for irrigation in terms of sodium-adsorption ratio, and specific conductance

The suitability of water for irrigation is dependent on two major factors or indicators; salinity and sodium-adsorption-ratio (Fireman and Hayward, 1955, p. 321). Salinity is dangerous to plants because it reduces the amount of water absorbed by the roots by increasing the osmotic pressure within the soil. Salinity is related to the specific conductance of water to an electric current.

The sodium-adsorption-ratio (SAR) is a measure of the amount of sodium ions present with respect to calcium and magnesium ions. If this ratio is high, sodium may be exchanged for calcium and magnesium adsorbed on the soil, which can destroy the soil structure and reduce permeability.

Figure 18 is a diagram helpful in evaluating water to be used for irrigation. It is divided into 16 areas, which categorize a water sample according to its potential for excessive salinity and ion exchange. Specific-conductance and sodium-adsoprtion-ratio were plotted for the three aquifer types. Bedrock well 124.48.26BAB was not included due to possible drilling-mud contamination. Results from figure 18 seem to indicate that water from the drift aquifers may present a salinity hazard. Water from the Cretaceous aquifer is considered very high in both salinity and sodium hazards.

Another constituent that may adversely affect the suitability of water for irrigation is boron. It is present in most natural ground waters in concentrations up to a few tenths of a milligram per liter (Hem, 1970, p. 188) and is essential to plant growth. Toxicity may develop, however, in semitolerant crops (for example, corn and sunflowers) when the concentration reaches 1 to 2 mg/L. The average boron concentration of water from Cretaceous rocks (2 samples) is 3.6 mg/L, which is considered unsuitable even for tolerant crops (Hem, 1970, p. 329).

Nitrate concentrations were higher in water from surficial deposits than from either the buried or bedrock aquifers. Water samples in two of the shallow wells approached the minimum limit for nitrate set by the U.S. Public Health Service (1962) and exceeded the limit by a factor of 5 in another. Sources of nitrate pollution might include livestock feed lots and heavily fertilized areas.

CONCLUSIONS

Test drilling in northwestern Big Stone County has located both surficial and buried outwash aquifers of Quaternary age and confirmed the presence of bedrock aquifers of Cretaceous age. A surficial deposit approximately 5 mi^2 in area is present southeast of Beardsley. The deposit, which is composed of sand and gravel and trends northeast-southwest, has a maximum saturated thickness of 42 feet. The theoretical maximum yield increases toward the axis of the deposit, reaching a value of 600 gal/min at Beardsley.

Buried aquifers occur over much of the project area, but are of small areal extent. A major sand deposit, just east of Beardsley, consists of 130 feet of fine sand overlain by 130 feet of clay till. This buried aquifer

lies in a steep-sided valley eroded in bedrock. The aquifer trends northwest-southeast. Aquifer-test results indicate that the transmissivity ranges from 10,800 to 13,400 ft^2/day, and the storage coefficient ranges from 0.0001 to 0.002.

Two Cretaceous aquifers have been identified, but little is known about their hydrologic properties. Domestic and stock wells completed in the Cretaceous rocks commonly yield about 15 gal/min.

Water from the surficial and buried outwash aquifers is hard (approximately 1,000 mg/L) relative to water from the Cretaceous rocks, but is suitable for domestic or irrigation uses. Wells in the Cretaceous aquifers, however, yield water with sodium concentrations that may damage soil structure and boron concentrations that would be toxic to most crops grown in the area.

Table 2 contains logs of 24 deep test holes drilled during this investigation. Land-surface altitudes were interpolated from a topographic map and are probably accurate to within about 3 feet of the actual value.

REFERENCES

Austin, G. S., 1972, Cretaceous rocks in geology of Minnesota: Sims, P. K., and Morey, G. B. eds.,: A Centennial Volume, Minnesota Geological Survey, p. 510.

Big Stone County Soil Conservation District, 1963, Land resources description of Big Stone County: unpublished report.

Cotter, R. D., Bidwell, L. E., Oakes, E. L., and Hollenstein, G. H., 1966, Water resources of the Big Stone Lake watershed, west-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-213.

Fireman, M., and Hayward, H. E., 1955, Irrigation water and saline and alkali soils: in the Yearbook of Agriculture - Water: U.S. Department of Agriculture, 84th Congress, 1st session, house document no. 32, p. 322.

Flint, R. F., 1955, Pleistocene geology of Eastern South Dakota: U.S. Geological Survey Professional Paper 262, 173 p.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473.

Krumbein, W. C., and Libby, W. G., 1957, Application of moments to vertical variability maps of stratigraphic units: American Association of Petroleum Geologists Bulletin, v. 41, no. 2, p. 197-211.

Leverett, Frank, 1932, Quaternary geology of Minnesota and parts of adjacent states, with contributions by F. W. Sardensen: U.S. Geological Survey Professional Paper 161, 149 p.

Matsch, C. L., 1972, Quaternary geology of Southwestern Minnesota, in Geology of Minnesota, Sims, P. K., and Morey, G. B. eds.: A Centennial Volume, Minnesota Geological Survey, p. 548.

Minnesota Pollution Control Agency, 1972, Minnesota State regulations; rules, regulations, classifications, and water standards: Minnesota Pollution Control Agency, Division of Water Quality, 150 p.

Shurr, G. W., 1979, Upper Cretaceous rocks at Lake Traverse in western Minnesota: U.S. Geological Survey Open-File Report 79-379.

Sims, P. K., and Morey, G. B., 1972, Geology of Minnesota: A Centennial Volume, Minnesota Geological Survey, 632 p.

Sloan, R. E., 1964, The Cretaceous system in Minnesota: Minnesota Geological Survey Report of Investigations 5, 64 p.

Thiel, G. A., 1944, The geology and underground waters of southern Minnesota: University of Minnesota: Minnesota Geological Survey Bull. 31, p. 97-105. 97-105.

U.S. Public Health Service, 1962, Drinking water standards, 1962: U.S. Public Health Service Publication 956, 61 p.

Winchell, N. H., 1901, Glacial lakes of Minnesota: Geological Society of America, v. 12, p. 109-28.

Winter, T. C., 1975, Delineation of buried glacial-drift aquifers: U.S. Geological Survey Journal of Research, v. 3, no. 2, p. 137-48.

Wright, H. E., Jr., 1972, Quaternary History of Minnesota, in Geology of Minnesota, Sims, P. K., and Morey, G. B., eds.: A Centennial Volume, Minnesota Geological Survey, p. 515.

Wright, H. E., Jr., Matsch, C. L., and Cushing, E. J., 1973, Superior and Des Moines Lobes: Geological Society of America, Memoir 136, p. 153-85.

Table 2.--Geologic logs of deep test holes

[Altitude in feet, based on National Geodetic Vertical Datum of 1929]

Material	Thickness (feet)	Depth (feet)
Deep test hole: BS-1 Location: 124.48.16.1BBB Alt: 1090		
Quaternary		
Sand, brown, coarse.....	13	13
Till, yellow.....	5	18
Till, gray, sandy.....	12	30
Till, with thin sand layers.....	60	90
Till, gray, sandy.....	123	213
Sand, gray, fine to medium, well sorted...	75	288
Cretaceous		
Carlile Shale.....	2	290
Deep test hole: BS-2 Location: 124.48.15AAA Alt: 1131		
Quaternary		
Till, yellow-brown, sandy.....	21	21
Till, dark brown.....	14	35
Till, gray.....	44	79
Gravel, fine, contains boulders.....	2	81
Till, gray.....	14	95
Sand, medium to coarse..	1	96
Till, gray, sandy.....	39	135
Sand, coarse.....	6	141
Sand, coarse, and interbedded gray clay.....	24	165
Till, gray, sandy.....	70	235
Sand, gray, coarse, grading to fine.....	23	258
Cretaceous		
Carlile Shale.....	43	301
Deep test hole: BS-3 Location: 124.48.13AAA Alt: 1110		
Quaternary		
Till, brown, sandy.....	18	18
Till, gray, sandy.....	88	106
Till, gray with black shale and dolomite fragments.....	25	131
Sand, coarse, with interbedded gray clay...	15	146
Sand and gravel.....	15	161
Sand and clay layers....	9	170
Till, gray, sandy.....	21	191
Sand, gray, medium, grading down to gravel.....	75	266
Cretaceous		
Carlile Shale.....	15	281

Table 2.--Geologic logs of deep test holes--Continued

Material	Thickness (feet)	Depth (feet)
Deep test hole: BS-4 Location: 124.49.35CCC Alt: 1094		
Quaternary		
Till, yellow, sandy.....	16	16
Till, gray, sandy.....	14	30
Gravel, fine, contains boulders.....	3	33
Till, gray.....	39	72
Sand(?).....	2	74
Till, gray.....	42	116
Sand, coarse.....	2	118
Till, dark gray with shale fragments.....	23	141
Deep test hole: BS-6 Location: 124.48.23DDD Alt: 1112		
Quaternary		
Till, yellow, stony.....	23	23
Till, gray, sandy.....	37	60
Till, gray, with coarse shale and dolomite fragments.....	52	112
Sand, gray, coarse; some gravel.....	4	116
Clay(?), gray.....	4	120
Sand, coarse.....	1	121
Till(?), gray, sandy.....	6	127
Boulder, granite.....	1	128
Till, gray, clayey.....	51	179
Sand and gravel, gray, poorly sorted.....	59	238
Cretaceous		
Carlile Shale.....	42	280
Deep test hole: BS-7 Location: 124.48.21DDD Alt: 1126		
Quaternary		
Till, yellow-brown, sandy.....	14	14
Till, gray, sandy, soft.....	46	60
Sand, fine with some gravel, poorly sorted.....	12	72
Till, gray, sandy, soft.....	22	94
Sand, fine to medium....	25	119
Till, gray, hard.....	16	135
Sand, gray.....	5	140
Till, gray, sandy.....	29	169
Sand, medium to coarse; some gravel.....	22	191
Till, gray, hard.....	14	205
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	15	220
Carlile Shale.....	20	240

Table 2.—Geologic logs of deep test holes—Continued

Material	Thickness (feet)	Depth (feet)
Deep test hole: BS-8 Location: 124.48.20CC Alt: 1086		
Quaternary		
Till, yellow, sandy.....	2	2
Sand and gravel.....	14	16
Till, gray, sandy.....	29	45
Sand, medium to coarse..	17	62
Clay(?), gray, sandy....	6	68
Sand, medium to coarse..	6	74
Clay(?).....	2	76
Sand, medium to coarse..	9	85
Till, sandy, soft.....	27	112
Till, gray, sticky.....	84	196
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	12	208
Carlile Shale.....	68	276
Greenhorn Formation.....	28	304
"Graneros" Shale.....	116	420
Deep test hole: BS-9 Location: 124.49.24CCC Alt: 1088		
Quaternary		
Till, yellow, sandy.....	17	17
Till, gray, sandy.....	20	37
Gravel, with some sand..	6	43
	6	43
Till, dark gray, hard...	27	70
Sand, medium to coarse..	4	74
Till, gray, sandy, stiff.....	26	100
Sand, fine to medium....	4	104
Till, gray, with thin sand layers.....	90	194
Sand.....	2	196
Clay(?), gray.....	9	205
Sand.....	4	209
Clay(?), soft.....	7	216
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	12	228
Carlile Shale.....	14	242
Deep test hole: BS-10 Location: 123.48.6BDC Alt: 1080		
Quaternary		
Sand and gravel, very coarse.....	33	33
Till, gray, stony.....	37	70
Sand, very coarse.....	7	77
Clay(?), gray.....	4	81
Sand, coarse.....	2	83
Clay(?), gray.....	4	87
Sand, coarse.....	2	89
Till, gray, sandy.....	103	192
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	18	210
Carlile Shale.....	68	278
Greenhorn Formation.....	30	208
"Graneros" Shale.....	50	358

Table 2.--Geologic logs of deep test holes--Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Deep test hole: BS-11			Location: 123.48.23CCC	Alt: 1079	
Quaternary			Cretaceous		
Till, yellow.....	28	28	Carlile(?) Shale.....	86	195
Sand, medium to coarse..	11	39	Greenhorn(?) Formation..	25	220
Till, gray, with sandy layers.....	54	93	"Graneros"(?) Shale.....	141	361
Sand and gravel.....	16	109			
Deep test hole: BS-12			Location: 123.47.31AAA	Alt: 1080	
Quaternary			Till, gray, sandy.....	80	200
Till, yellow.....	15	15	Cretaceous		
Till, gray.....	21	36			
Sand.....	1	37	Codell Sandstone Member of Carlile Shale.....	20	220
Till, gray, sandy.....	46	83	Carlile Shale.....	40	260
Sand, gravel, and clay, interbedded.....	33	116	Greenhorn Formation.....	18	278
Sand.....	4	120	"Graneros" Shale.....	43	321
Deep test hole: BS-13			Location: 123.48.16CCC	Alt: 1114	
Quaternary			Sand, very coarse.....	2	142
			Till, dark gray.....	90	232
Till, yellow, sandy.....	24	24			
Till, brown.....	3	27	Cretaceous		
Till, gray, sandy.....	9	36			
Sand, coarse.....	2	38	Codell Sandstone Member of Carlile Shale.....	18	250
Till, gray, with thin sand layers.....	52	90	Carlile Shale.....	74	324
Sand and gravel.....	22	112	Greenhorn Formation.....	24	348
Till, gray, sandy.....	28	140	"Graneros" Shale.....	13	361

Table 2.--Geologic logs of deep test holes--Continued

Material	Thickness (feet)	Depth (feet)
Deep test hole: BS-14 Location: 124.48.33DDD Alt: 1125		
Quaternary		
Till, yellow, stony.....	20	20
Till, brown, sandy.....	11	31
Sand and gravel, coarse.....	7	38
Clay(?), brown.....	7	45
Sand, coarse.....	4	49
Clay(?), brown.....	12	61
Till, gray.....	29	90
Till, gray and sandy....	38	128
Sand.....	7	135
Till, gray, with sand and boulders.....	101	236
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	6	242
Carlile Shale.....	71	313
Greenhorn Formation.....	24	337
"Graneros" Shale.....	64	401
Deep test hole: BS-15 Location: 124.48.18BBB Alt: 1093		
Quaternary		
Till, yellow, stony.....	19	19
Sand, gray, coarse.....	9	28
Till, gray, soft.....	13	41
Sand and gravel, coarse.....	8	49
Clay(?), gray, soft, silty.....	6	55
Sand, very fine, dirty..	21	76
Till, gray, with some sandy layers.....	122	198
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	15	213
Carlile Shale.....	64	277
Greenhorn Formation.....	30	307
"Graneros" Shale.....	24	331
Deep test hole: BS-16 Location: 124.48.16DDD Alt: 1126		
Quaternary		
Till, yellow, stony.....	26	26
Sand and gravel.....	16	42
Till, gray, silty.....	14	56
Sand, coarse, interbedded with clay.....	4	60
Sand, black, shaley, coarse.....	16	76
Clay(?).....	2	78
Sand.....	2	80
Till, gray, soft, sandy.	80	160
Till, gray, with thin sand layers.....	60	220
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	14	234
Carlile Shale.....	64	298
Greenhorn Formation.....	26	324
"Graneros" Shale.....	77	401

Table 2.—Geologic logs of deep test holes—Continued

Material	Thickness (feet)	Depth (feet)
Deep test hole: BS-17 Location: 124.48.4BBB Alt: 1165		
Quaternary		
Till, yellow, stony.....	30	30
Till, gray, soft, sandy.....	100	130
Sand, medium to coarse, dirty.....	20	150
Sand and gravel, very coarse.....	9	159
Sand, fine with some clay.....	6	165
Till, gray, sticky.....	42	207
Sand, gray, very fine...	12	219
Clay(?).....	6	225
Sand, medium to coarse, with some clay layers..	15	240
Till, gray.....	30	270
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	10	280
Carlile Shale.....	60	340
Deep test hole: BS-18 Location: 124.48.3AAA Alt: 1135		
Quaternary		
Till, yellow.....	34	34
Till, gray, sandy, soft.....	39	73
Sand, coarse.....	1	74
Till, gray, with thin gravel layers.....	104	178
Sand, very coarse, with clay layers.....	17	195
Cretaceous		
Carlile(?) Shale.....	104	299
Deep test hole: BS-19 Location: 124.48.12BBB Alt: 1123		
Quaternary		
Till, yellow, soft.....	14	14
Till, gray, soft.....	110	124
Sand, coarse.....	6	130
Till, gray, silty.....	15	145
Sand, medium to coarse..	2	147
Clay(?).....	3	150
Sand, fine to coarse....	6	156
Till, brown, gravelly...	44	200
Sand, medium, with some gravel.....	39	239
Clay(?).....	5	244
Sand.....	4	248
Clay(?).....	12	260
Sand, fine.....	8	268
Cretaceous		
Carlile Shale.....	17	285
Greenhorn Formation.....	27	312
"Graneros" Shale.....	9	321

Table 2.--Geologic logs of deep test holes--Continued

Material	Thickness (feet)	Depth (feet)
Deep test hole: BS-20 Location: 124.49.1AAA Alt: 1115		
Quaternary		
Till, yellow-brown, silty	55	55
Till, gray	23	78
Sand, very fine, some clay	27	105
Sand and clay layers	7	112
Till, gray, sandy	116	228
Cretaceous		
Codell Sandstone Member of Carlile Shale	16	244
Carlile Shale	16	260
Deep test hole: BS-21 Location: 124.48.33BBB Alt: 1109		
Quaternary		
Till, yellow, stony	26	26
Sand and gravel, brown	8	34
Till, gray	8	42
Sand, very fine, dirty	11	53
Till, gray	16	69
Sand, gray, fine	17	86
Sand, black, coarse, shaley	1	87
Till, gray, soft	8	95
Sand, fine, dirty	15	110
Sand and gravel	5	115
Till, gray, hard, with boulders	91	206
Cretaceous		
Codell Sandstone Member of Carlile Shale	15	221
Carlile Shale	12	233
Deep test hole: BS-22 Location: 124.48.23AAA Alt: 1089		
Quaternary		
Till, yellow, sandy	20	20
Till, gray, gravelly	18	38
Sand, coarse	3	41
Till, gray, stony	36	77
Sand, very fine	6	83
Clay(?), gray	6	89
Sand and gravel	5	94
Till, gray, hard	22	116
Gravel and interbedded clay, gray	20	136
Sand, quartz, gray, fine, well sorted	131	267
Cretaceous		
Carlile Shale	6	273
Greenhorn Formation	19	292
"Graneros" Shale	68	360

Table 2.--Geologic logs of deep test holes--Continued

Material	Thickness (feet)	Depth (feet)
Deep test hole: BS-24 Location: 124.48.27AAA Alt: 1095		
Quaternary		
Till, yellow, stony.....	17	17
Sand, brown, coarse.....	2	19
Till, yellow.....	2	21
Till, gray, sandy.....	24	45
Sand, coarse, shaley....	9	54
Till, gray, soft.....	16	70
Sand, fine, dirty.....	8	78
Gravel, medium.....	12	90
Gravel and interbedded clay.....	10	100
Sand, fine, and interbedded clay.....	20	120
Till, gray, soft.....	58	178
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	10	188
Carlile Shale.....	69	257
Greenhorn Formation.....	24	281
"Graneros" Shale.....	10	291
Deep test hole: BS-25 Location: 123.48.1ABB Alt: 1130		
Quaternary		
Till, yellow.....	12	12
Till, brown.....	4	16
Till, gray, soft, sandy.....	96	112
Sand, very coarse.....	8	120
Boulders.....	5	125
Gravel, very coarse, with some pebbles.....	10	135
Clay(?), soft.....	5	140
Sand and gravel.....	1	141
Till, gray, soft, sandy.....	79	220
Cretaceous		
Codell Sandstone Member of Carlile Shale.....	10	230
Carlile Shale.....	27	257
Deep test hole: BS-26 Location: 124.47.19BAB Alt: 1114		
Quaternary		
Till, yellow, stony.....	16	16
Till, gray, very soft...	80	96
Till, with coarse sand layers.....	45	141
Sand, coarse, with clay layers.....	10	151
Gravel, coarse, with boulders.....	30	181
Gravel, with thin clay layers.....	14	195
Gravel, very coarse, cobbles.....	6	201